MANAGEMENT OF BUILDING ENERGY CONSUMPTION AND ENERGY SUPPLY NETWORK ON CAMPUS SCALE

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[To Dad and Mom always cheered me up in heaven]

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TABLE OF CONTENTS

LIST OF TABLES

Page

LIST OF FIGURES

Page

LIST OF SYMBOLS AND ABBREVIATIONS

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BIPV	Building Integrated Photovoltaic
CEN	European Committee for Standardization
CHP	Combined Heat and Power
DCP	District Cooling Plant
DHP	District Heating Plant
DOE	Department of Energy
eGRID	The Emissions and Generation Resources Integrated Database
EPC	Energy Performance Coefficient
EPSCT	Energy Performance Standard Calculation Toolkit
HVAC	Heating, Ventilation, and Air Conditioning
IEA	International Energy Agency
ISO	International Organization for Standardization
NEP	Network Energy Performance
PV	Photovoltaic
R-C	Resistance-Capacitance
E_{del}	Delivered Energy
E_p	Primary Energy
Q_{nd}	Thermal Energy Need

SUMMARY

Building portfolio energy management at the campus or larger scale involves decisions about energy retrofits, energy resource pooling, and investments in shared energy systems, such as district cooling, community photovoltaics (PV), wind power, combined heat and power (CHP) systems, and/or geothermal systems, among others. There are currently no tools to help a portfolio or campus manager make decisions about these issues through a rapid comparison of variants. In order to improve the design of large-scale building energy systems, regional policy makers and environmental administrators require knowledge of expected energy use and emissions on a large-scale , together with the ability to predict the outcomes of ongoing efficiency changes as well as new policies imposed on the building sector.

Network Energy Model Development:

This thesis develops a model for energy performance assessment to support energy efficient design at district scale focusing on the multiple relationships between energy consumers and producers in the district. The model uses (1) a building energy model to quantify the energy performance of buildings as energy consumers on an hourly basis, and (2) network to analyze energy flows and quantify the overall performance of a wide variety of energy supply systems shared by buildings (energy consumers).

The network energy model represents energy consumers and energy producers on the community level, allowing alternative ways to connect them in an overall energy supply topology. The essence of the model is a directed graph, consisting of nodes and connectors (arcs). A node represents an energy consumer or producer and arcs represent ways in which they are connected. Arcs come in different types, each type representing a particular way in which a supplier and consumer can be connected. Building nodes

represent energy consumers at the highest level. At a lower level, a building node contains sub-nodes that represent the individual consumer systems (heating, cooling, lighting, fans, pumps, domestic hot water, and other services) in a building. Producer nodes represent various electrical power and thermal energy supply systems, including power generation from fossil fuel power plants (this is typically an external node), renewable source systems and thermal energy distribution from district heating and cooling systems, in conjunction with combined heat and power plants. After a graph is constructed and all properties of the system nodes are provided, the calculation runs in the background and shows energy consumption and generation at the network level as well as the node level in a given climate. Each arc that crosses a node represents a quantity of purchased or delivered energy flowing to or from the node.

Research Focus:

The NEP model allows campus wide energy performance assessment testing different supply topologies, i.e. which consumer nodes connect to which local suppliers and which connect to global suppliers (i.e. utility providers such as the electricity grid or the natural gas grid). The prototype implementation shows how a portfolio or campus manager defines a model of the consumer and supply nodes on a campus and manipulates the connections between them through a graphical interface. Every change in the graph automatically triggers an update of the energy generation and consumption pattern, and results in a campus-wide energy performance update. It helps macro decisions on the generation side (such as decisions about adding campus wide systems) and the consumption side (such as planning of new building designs and retrofit measures).

This model provides a lightweight tool that supports rapid decision making for energy efficient system design on a portfolio scale in the building sector. There is no deep simulation required as the goal is to manage macro design decisions, not micro operational decisions. The premise of this approach is that an energy performance assessment of each node, based on normative calculation methods, is accurate enough to support macro, system-level decision making. The model is scalable to larger portfolios and systems, and is flexible enough to explore different topologies by adding or taking away nodes. The main distinguishing feature is the way that nodes and their connections can be managed in the graphical interface while the underlying representation maintains the consistency to perform fresh calculations at any time. Compared to approaches used in the smart grid or GIS field (mostly based on statistical models with few categorical variables per node), the approach here deploys a more accurate and more configurable model. Compared to models for operational building energy management (typically based on real time embedded simulation), the approach uses a lightweight, more flexible approach that avoids intensive simulation.

The energy performance quantification of buildings, energy supply and energy generation systems bring rich information to decision makers who will be well-positioned when they seek reductions in primary energy consumption and greenhouse gas (GHG) emissions. The model helps energy efficient system design based on system-wide outcomes, consequently achieving energy savings in the building sector and avoiding negative environmental impacts. A major benefit resulting from the research is that it has the capability to support decision making in large-scale building sector energy policy planning, i.e. beyond campus scale such as on a metropolitan scale.

The research hypothesis of the thesis is “the NEP model supports decision making in a large-scale building energy system design” with aspects of:

- Convenience: right engineered model
- Optimality: making the right decision

The thesis shows how the NEP model supports decision making with respect to large-scale building energy system design with a case study of the Georgia Tech campus evaluating the following three assertions:

1. The normative calculations at the individual building scale are accurate enough to support the network energy performance analysis

2. The NEP model supports the study of the tradeoffs between local building retrofits and campus wide energy interventions in renewable systems, under different circumstances

3. The NEP approach is a viable basis for routine campus asset management policies

CHAPTER 1

INTRODUCTION

1.1 Why Energy Efficiency in Buildings

Energy consumption and its accompanying carbon emissions have increased substantially in recent decades. Reports by the IEA World Energy Outlook Reference Scenario and the IPCC scenario studies report a rise in global emissions and warn that such emission profiles will put the world in a dangerous environmental situation (IEA, 2006; UNEP & WMO, 2000). If current trends are not changed, the resulting temperature rise is expected to be as high as 3 – 4 degree Celsius by 2100 and up to 6 degree Celsius by 2300 (WBCSD, 2005). The building sector consume more than 40% of the world's primary energy, making buildings the largest category of energy users, and this accounts for 24% of world CO_2 emissions (UNEP, 2007). The carbon emissions resulting from energy consumption by the building sector are substantially greater than those in the transportation sector (WBCSD, 2009). Increased energy consumption in buildings is the result of a growing service economy requiring more commercial buildings, a shift from rural to urban living, and the proliferation of electricity using appliance and systems. To overcome the potential environmental crisis, vigorous research programs are in place at the governmental level to development policies for energy reduction in the building sector. Major research focuses on:

- Improving the energy performance of buildings (EU, 2011)
- Development of new technologies and practices for energy efficiency (DOE, 2011)

Research in the field of the energy performance and efficiency has become a priority. When we want to understand where and how we can increase efficiency in the building sector, energy performance assessment is crucial. This is closely related to new building energy rating methods, which are required for the development of related building policies.

1.2 Energy Performance Assessment and Rating

To achieve energy efficiency in buildings, the systematic and objective evaluation of the energy performance of every new and existing building is necessary. The evaluation of individual buildings supports decisions about individual building improvement and will inform ongoing energy and environmental policy development. The European Union and its Energy Performance in Buildings Directive (EPBD) has focused on methodologies for calculating and rating the energy performance of new and existing buildings (European Commission, 2002). This has brought the European Committee for Standardization (CEN) and the International Organization for Standardization (ISO) together to develop international standards, such as ISO 13790:2008 (ISO, 2008), for the standardized calculation of building energy performance. This standard defines the calculation "recipe" according to a set of normative statements about functional building category, assumed usage scenarios, system efficiency, etc. Through its simplicity and unified modeling assumptions this approach forms the basis for assessing building energy performance in a standardized and transparent way (Hogeling & Dijk, 2008).

The calculation method is specified as an algebra over a set of parameters, that is, a set of algebraic equations where some "model" parameters are derived from observable building design parameters while other parameters are derived through empirical equations specified in the standard. This methodology responds to the problems with dynamic simulation (indeed, there is no simulation tool that would allow a fully transparent calculation method that rules out modeler's bias). Obviously this raises the question of how accurately the algebra approximates the actual energy use, and how well the (in many cases macro) parameters in the calculation reflect the actual physical behavior of the (micro) physics of the building. This is an interesting question but not always the most relevant question. After all, a standardized expression of performance does not need a prediction of actual energy consumption (or the best approximation of it) as it only needs to guarantee that the resulting Energy Performance Coefficient (EPC):

$$EPC = \frac{Energy\ Calculated}{Energy\ Referenced}$$

is an objective measure for the energy performance. As the equation shows, the EPC is normalized by proper definition of a reference value, E_{ref} for every functionally equivalent building type. The correlation between the normative outcome and simulated energy consumption have indeed been studied and results thus far are proof enough to accept the approach as good enough to accept the calculated EPC as objective indicator of performance (Augenbroe & Park, 2005; Beerepoot & Beerepoot, 2007; González, Díaz, Caamaño, & Wilby, 2011).

In the standard EN 15603 [21], CEN proposes two types of ratings: (1) calculated ratings, based on computer calculations to predict energy used by a building for HVAC systems, domestic hot water and lighting and (2) measured (or operational) ratings, based on real metering on-site. Calculated ratings are subdivided into standard (also called asset) and tailored ratings. The asset ratings use the calculation procedure within standard usage patterns and climatic conditions not to depend on occupant behavior, actual weather and indoor conditions, and are designed to rate the building and not the occupant (Pe´rez-Lombard, Ortiz, lez, & Maestre, 2009).

As with any normative method, this method also raises important fairness concerns. For instance, a building may use special energy saving measures or technologies that may not get the credit they deserve in the calculation method. Not surprisingly, all standardization bodies that mandate the use of the normative standard in their building code are concerned about this issue. In fact, manufacturers and designers line up to claim energy benefits, the benefit of which the calculation does not reflect. Some countries leave a "back door option" open, which is to allow using simulation in such cases. This obviously negates many of the benefits of the normative approach. A better way forward would be to continuously update the calculation to better account for certain design measures and technologies.

The second pillar in the philosophy is less contentious. Indeed, for normative energy labeling it should not matter how the building is used by the client because the rating is meant to label the building, not the combination of building and client. Understanding the difference is easy in the example of car ownership. Assume that person A has a fuel efficient car, usually drives alone, and drives about 20,000 mile per year. Person B has a "gas guzzler," but always drives with his family of four and drives only 10,000 miles per year. Two interesting questions can be raised: (1) which car is more efficient; (2) which car is used more efficiently? These questions will not be answered here, but it is obvious that the answers to them will be different. So it is essential that in evaluating rating methods, one has a clear perspective on what is to be rated. In the case of buildings, the starting point in this study is that the building should be rated, and that will also form the baseline of the application studies. It should be noted that the building simulation discipline often laments that their results are often not confirmed by real data because they could not foresee how the building was actually going to be used. Here it is argued, based on the above statement, that such comparisons are futile as rating a design should not be dependent on the assumptions about the building's use. This is another good reason to use a normative rating method.

A building energy rating system therefore defines the energy performance under standard conditions. For a new building, the EPBD framework determines the energy rating based on the calculated energy use following the calculation procedure for a standard usage pattern and climatic condition (CEN, 2008). The approach is designed to rate the buildings and not the occupants. Thus, the calculated building energy rating does not depend on actual conditions of occupant behavior and weather (Pe´rez-Lombard et al., 2009). It should be obvious the assumed standard usage profile does not matter much as it is normalized through the appropriate choice of E_{ref}.

It is worth noting that building energy performance quantification for existing buildings as well as new designs is identical. In both cases one would work from the design specifications.

The calculation method has been validated through a number of rigorous validation efforts (Burhenne & Jacob, 2008; Jokisalo & Kurnitski, 2007; Georgios Kokogiannakis, Strachan, & Clarke, 2008; G. Kokogiannakis & Strachan, 2007; Orosa & Oliveira, 2010; Ruiz-Pardo & Ferna´ndez, 2010; Siren & Hasan, 2007).

Another factor getting increasing attention, and rightly so, is the role of uncertainties. Simulation creates a virtual model that reflects many modeling assumptions and simplifications (made by the modeler and by the software developer) that introduce uncertainties. Other studies cited above have looked at the impact of these uncertainties on the calculated energy consumption, and in general they have found that these uncertainties have a significant impact. An ongoing major study has set out to quantify uncertainties at different scales and determine their relative impact on energy performance predictions. An important goal of that study is to compare the confidence levels in energy performance outcomes obtained with the normative method, compared to simulation based methods (Lee, Zhao, & Augenbroe, 2011). Based on currently available work, it is to be expected that normative models will produce a higher level of confidence, in spite of their deficiencies in not being able to represent all building and system features.

Combined with the fact that the normative calculation approach has advantages of easiness, transparency, robustness, and reproducibility, it provides the best way forward for energy performance rating and, in fact, the approach has many additional application areas.

1.3 The Unit of Energy Performance Assessment

To cover an extended scale of urban / campus energy topology, an energy performance assessment methodology requires first of all an effective and integrative performance assessment model. Gradually enlarging scales need to be considered and decisions need to be supported at any scale. Multi-scale complex energy systems pose difficulties in mastering all the knowledge required for efficient system design and topologies in the building sector (Caudana, Conti, Helcke, & Pagani, 1995).

Relying on monitored data is not an option. The detailed, consistent, and timely data necessary are not available for a comprehensive analysis to construct effective energy saving plans on large-scale energy carriers and end-uses (Miranda-da-Cruz, 2007). Moreover, utility providers collect only data at the whole building scale. It is virtually impossible to properly attribute the share of overall consumption to individual consumer types in a building when adequate sub-metering is not installed. On university campuses things are typically even more difficult. Groups of adjacent buildings are metered as a group, and often buildings are connected to a district heating or cooling network without provisions for measuring the consumption of individual buildings. The ultimate way to understand the actual operating energy performance is to gather data from installed sub-meters for every individual consumer, but this is typically not cost effective to do retroactively. The development of energy performance models deserves more attention because they represent ways to discover the desirable characteristics of energy performance with standardized energy Performance Indicators (PIs) (Koretsune et al., 2005).

There are many independently operating components in a campus energy network. At a building scale, local HVAC systems as well as a variety of energy consuming appliances and systems in buildings plus the physical characteristics and operation patterns of buildings have a combined effect on energy consumption and efficiency. Secondly, on a larger scale, the resources and technologies of power plants, energy delivery methods, and energy grid systems are highly variable. At the larger scale, the individual building energy performance needs to be dealt in the context of an integrated network, taking into account the energy supply type, energy grid system, renewable energy generation, and primary resource power plant.

On this research, the CEN/ISO approach is followed. This defines the following building energy performance indicators: energy need, delivered energy (expected energy usage of each energy consumer), primary energy, and CO_2 emission. These indicators represent the energy performance of individual buildings. They form the basis for the aggregation of the overall campus assessment. Figure 1 illustrates the process of energy performance assessment from a building level to a large-scale considering different energy supply topologies. Chapter 2 explains the calculation method for the building level which is implemented in the energy performance standard calculation toolkit (EPSCT). Chapter 3 deals with large-scale energy supply including campus local and global systems and their calculation method. Chapter 4 explains the network energy performance (NEP) model integrating energy consumers and suppliers for overall energy performance in different topologies.

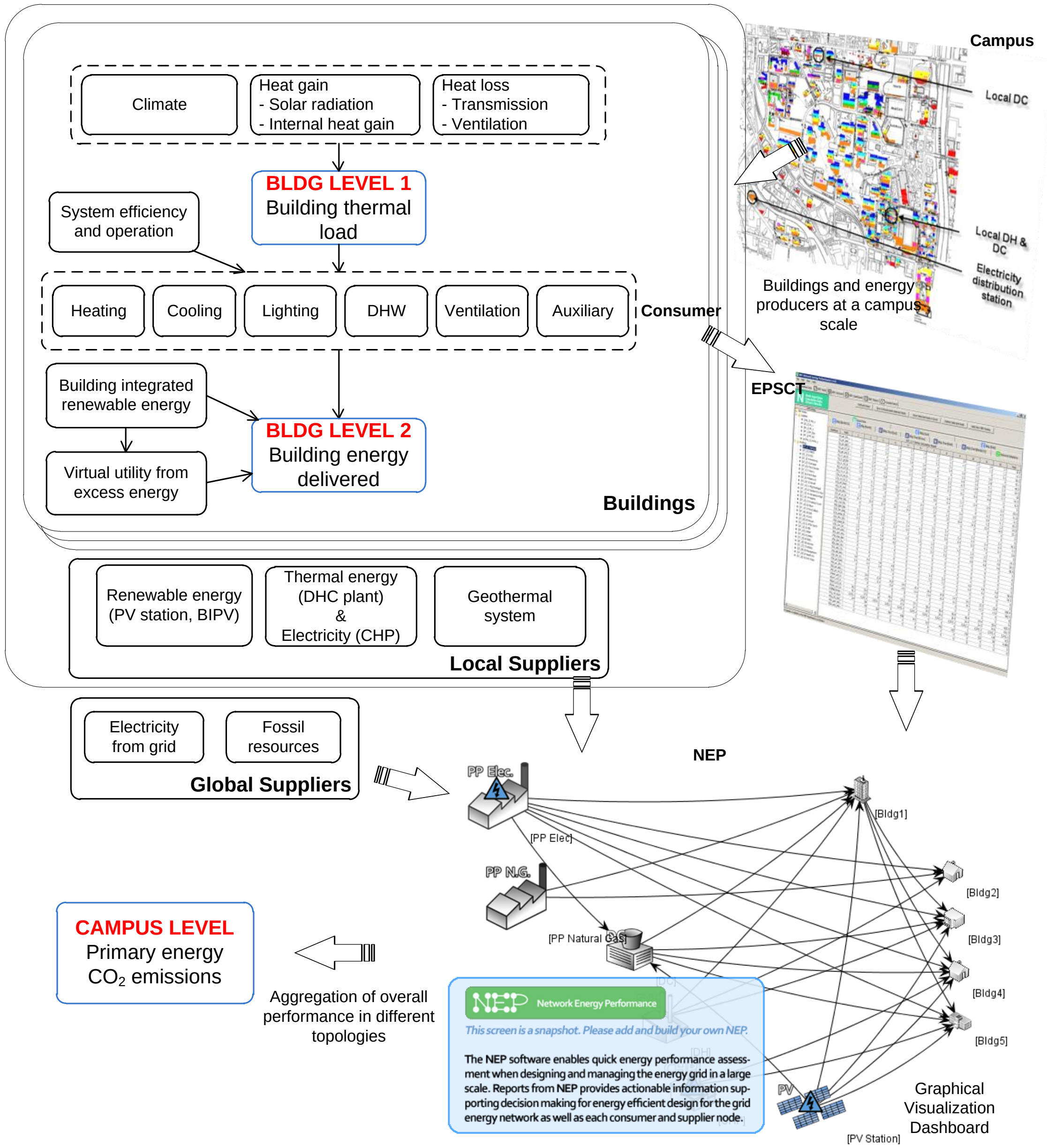


Figure 1 NEP System Diagram

CHAPTER 2

BUILDING LEVEL AN ENERGY PERFORMANCE ASSESSMENT FRAMEWORK

2.1 Energy Performance Assessment Method

There are two major approaches to analyzing building energy performance. One is using the normative calculation method, and the other is based on transient dynamic simulation method.

2.1.1 The Normative Calculation Method

Building energy performance relates specifically to the objective performance in relation to the uses of the building. It requires calculation of the thermal energy demand of a building with a special regard to a normative reference level of heat gains and losses, occupancy, system controls, and system efficiencies (ISO, 2008). In addition to the thermal energy demand, the total building consumption is defined as the sum of energy uses for heating, ventilation, lighting, pumps, cooling, (de)humidifying and preparation of domestic hot water in building installations. The advantage of this approach is that it declares performance indicators calculated directly from the relevant set of building and operation parameters. Although the resulting values cannot be taken as accurate absolute measures for an observable physical variable, the approach is accurate enough to estimate expected energy performance (Augenbroe & Park, 2005). The normative calculation approach has the advantages of simplicity, transparency, robustness, and reproducibility

(Dijk & Spiekman, 2007). Currently, the CEN standards are widely applied in EU countries (Hogeling & Dijk, 2007).

2.1.2 The Simulation Method

By contrast, building energy simulation requires dynamic computer modeling and techniques for analysis of building energy performance. The thermal load is calculated to determine the energy behavior of the building systems. A building energy model is created so that professionals can specify in detail the parameters which influence the building energy behavior. Energy simulation requires an hour by hour simulation of the entire building based on information about thermal properties of the envelope, control set points, occupant loads, primary and secondary HVAC system properties, and hourly weather data for the location of the building. In energy performance assessment with simulation, the goal is to predict energy use in a way the reflects what is expected of a real system as closely as possible (Clarke, 2001). A building energy simulation is typically effective for the design of controls, deep energy auditing and commissioning, and the optimum design of system components. However, simulation is time consuming and at larger scales it becomes impractical. Although simulation creates a detailed energy model that reflects a real design, it cannot resolve uncertainties that stem from assumptions and simplifications which are built into the simulation application (Birta & Arbez, 2007). In light of this, it is highly questionable whether simulation adds any benefit over normative calculations in campus energy management. This is addressed by hypothesis an energy performance assessment of each node by the normative method is accurate enough to support macro, system-level decision making.

2.1.3 The Selected Approach for Building Energy Assessment

Normative building energy performance assessment methods are, in contrast to simulation-based assessments, objective and typically specified in energy standards. The major performance-based approach is the one endorsed by the European Committee for Standardization (CEN) energy standards. It is based on a calculation "recipe" following the framework of a set of calculation standards (CEN/BT/TF 173, 2006). The performance-based approach allows building designers maximum freedom for innovative design, since they only specify the maximum allowable energy consumption level of the whole building (Augenbroe & Park, 2005). This approach forms the basis to assess building energy performance by an easy and transparent method. It is performance based and will not mandate specific product properties but will encourage development of energy efficient building products that influence the total outcome in a positive way.

The ISO approved the development of an international energy standard in early 2008. Issues such as significantly increased energy consumption, global environment protection, and the reduction of "carbon footprints" have generated strong interest in developing such an international standard. The energy standard development by the ISO provides an authoritative and practical approach to increasing energy efficiency and improving environmental quality by addressing the technical aspects of rational energy use by all types of organizations. The main features will be a logical and consistent methodology for achieving continual increases in energy efficiency, guidance on benchmarking, and promotion of new energy efficient technologies (Tranchard, 2008). ISO standard will apparently take over the main functions of the CEN energy standards, and with that the energy performance assessment based on the normative calculation is expected to be the mainstream approach for future energy standards. The implementation of the EPBD, the CEN energy standard has as its primary aim to establish an energy performance assessment method and rating system to guarantee energy savings and to reduce CO_2 emission (Rey, Velasco, & Varela, 2007). The calculation of building energy performance will be guided by standards that take into account building insulation, the characteristics of technical systems and installed equipment, the position and orientation of the structure for the purposes of climatic calculations, exposure, its own capacity for renewable energy sources, and other factors that influence the energy requirements of the building (Santoli & Matteo, 2003).

For the NEP model development, the normative calculation approach guided by the CEN/ISO standards is chosen for the underlying calculation method at the building scale. The following section introduces the energy performance standard calculation tool (EPSCT), a computer translation of the CEN/ISO standards. EPSCT is used for various energy performance research efforts including the network energy performance model used in this thesis used to calculate energy performance of an individual building. The NEP architecture aggregates the individual buildings models into the consumers/producers network.

2.2 Energy Performance Standard Calculation Toolkit (EPSCT)

EPSCT is an energy performance assessment toolkit embedded in the NEP model, and it has been developed for the hourly normative calculation method as defined in the ISO 13790 standard and supporting documents. The standard introduces a monthly quasi-steady-state and a simple hourly method for the calculation of the energy need for space heating and cooling for residential and non-residential buildings (Van Dijk, Spiekman et al. 2005). In addition to the thermal energy demand for heating and cooling, total building consumption is determined as the sum of energy consumed for heating, ventilation, lighting, pumps, cooling, (de)humidifying and preparation of domestic hot water in building systems. Supporting calculation standards are EN ISO 13789 for transmission and ventilation heat transfer, EN 15241, EN 15242 for ventilation for buildings, EN 15243 for cooling and ventilation systems, EN 15193 for lighting, EN 15316-3 series for domestic hot water, and EN 15316-4 series for heating systems. This section describes the set-up of the calculations and details a number of extensions to this set-up.

Figure 2 shows how the energy calculation flows. The major components impacting building energy efficiency are the thermal envelope, HVAC systems, controls, heat recovery application, and heat gains from building operation and location. The bottom row indicates the input data, consisting of the building characteristics, usage and climatic parameters. The upper part adds building system and controls to the building energy needs in order to calculate the expected value of delivered energy based on the total energy consumed by building operation.

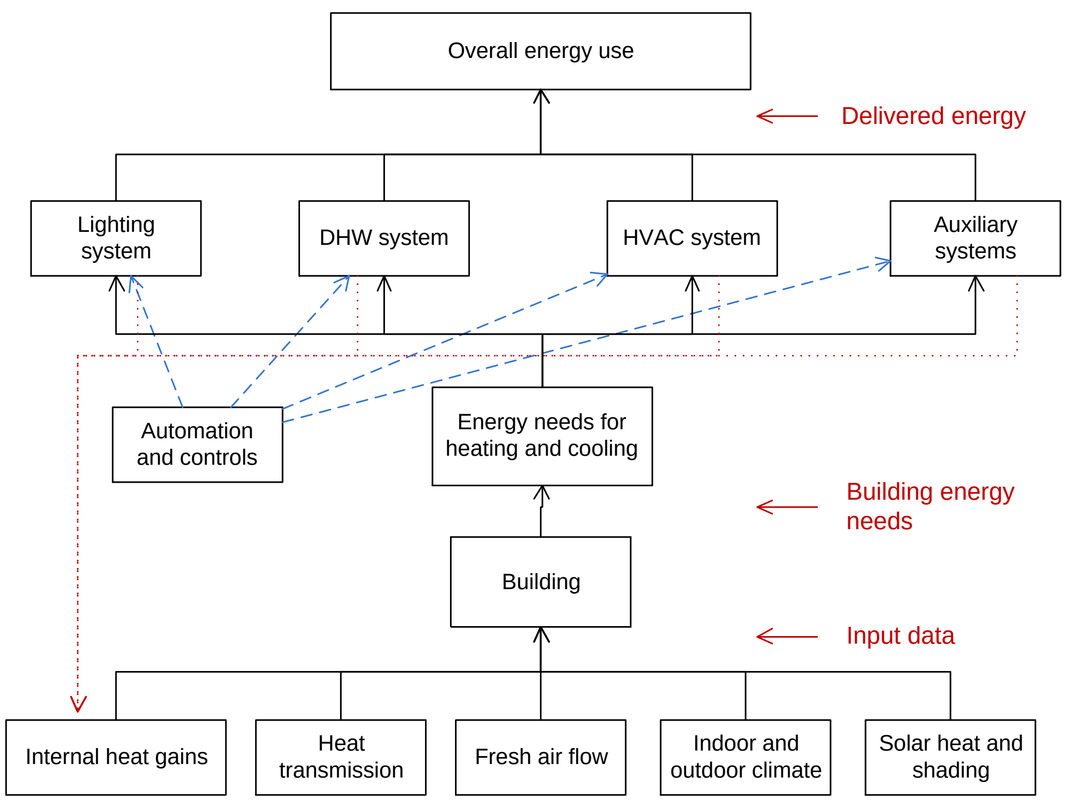


Figure 2 Energy Calculation Flows

2.2.1 Normative Calculation Method: Simple Hourly Method

The CEN / ISO standards prescribe the energy performance calculation method. There are two basic types of calculation method. One is a quasi-steady-steady method, calculating the heat balance over a monthly or seasonal time period. Some consideration for dynamic effects is given through the gain and /or loss utilization factor that is part of the calculation (internally derived from internal mass level). The other is a simple hourly “dynamic” method. The “dynamic” method calculates the heat balance using short time intervals taking into account the heat stored in, and released from, the mass of the building. Typically, the time interval is one hour, and the simple hourly “dynamic” calculation method is fully prescribed by the ISO 13790 standard.

This research uses the simple hourly “dynamic” calculation method which facilitates direct introduction of hourly usage patterns within the structure of the standard calculations, modeling heat transfer by thermal transmission and ventilation, thermal storage, and internal and solar heat gains. This facilitates the study of hourly based user behaviors and schedules such as temperature set-points, ventilation modes, and the operation schedules of solar shading controls. The simple hourly method is based on the simplified heat transfer between the internal and external environment using an equivalent resistance-capacitance model which has five resistances (Hve, Htr,w, Htr,em, Htr,ms, and Htr,is) and one capacitor(Cm). The model is illustrated in Figure 3.

The model makes a distinction between the internal air temperature and the mean radiant temperature of internal surfaces which increases the accuracy of the solar and internal heat gains. The heat transfer between the internal and external environment determines the need for heating and cooling power to maintain a heating and cooling set-point temperature for each hourly time step. The internal set-point temperature is a weighted mean of internal air and surface mean radiant temperature.

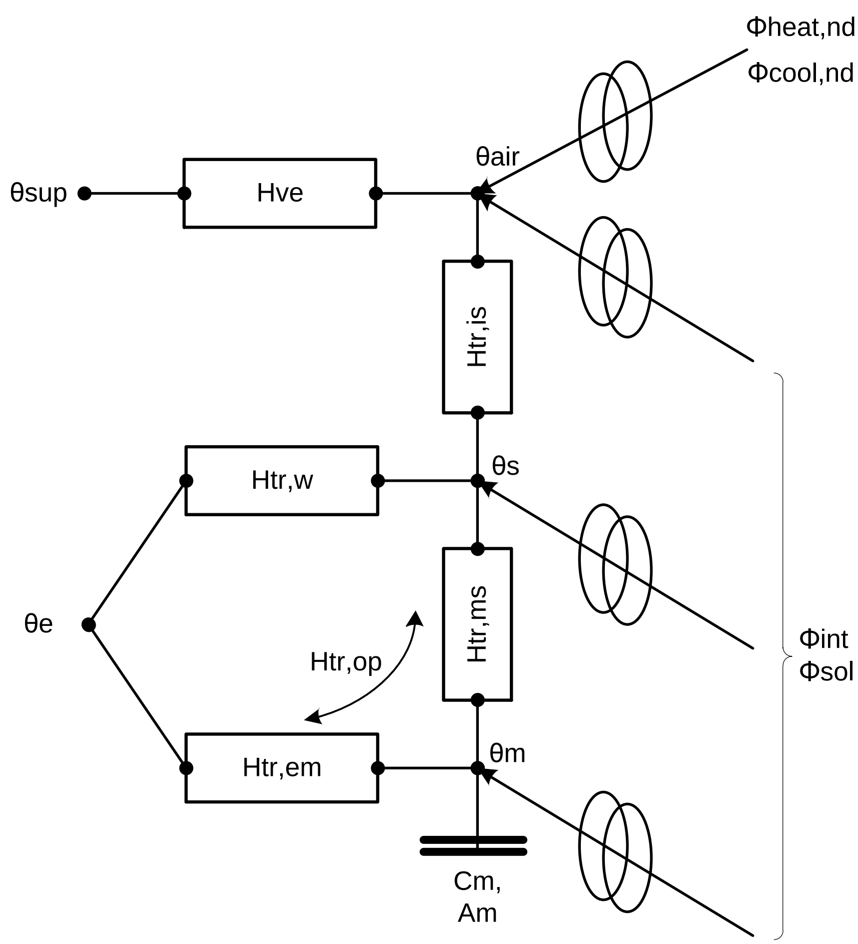


Figure 3 R-C model for Simple Hourly Dynamic Calculation Method

H_{ve} is the ventilation coefficient;

$H_{tr,w}$ is the thermal transmission coefficient from windows;

$H_{tr,op}$ is the thermal transmission coefficient from opaque surfaces;

$H_{tr,em}$ is the thermal transmission coefficient from the environment to the mass;

$H_{tr,ms}$ is the coupling conductance between the mass and the surface node;

$H_{tr,is}$ is the coupling conductance between the internal air node and the surface node;

θ_{sup} is the supply air temperature;

θ_e is the external dry bulb air temperature;

θ_m is the mass temperature;

θ_s is the central node temperature;

θ_{air} is the internal air temperature;

C_m is the internal heat capacity;

A_m is the effective mass area;

$\emptyset_{int}$ is the heat flow rate from internal heat sources;

$\emptyset_{sol}$ is the heat flow rate from solar heat sources;

$\emptyset_{heat,nd}$ is the heating demand;

$\emptyset_{cool,nd}$ is the cooling demand.

Heat transfer by ventilation is connected directly to the internal air temperature node with the supply air temperature. Heat transfer by transmission has two nodes: window and opaque. The window part does not have a thermal mass. The opaque part contains thermal mass, and it is split into two coefficients of external to mass and mass to internal surface. The central node represents a mix of the internal air temperature and mean radiant temperature. The thermal mass is located between the external node and the central node. Solar and internal heat gains are distributed over the internal air node, central node, and the mass node. Then from the all defined values, this simple hourly dynamic model calculates the heating and cooling energy need as well as the internal air temperature for a given hour.

The heat balance model applied in the thesis for the building level energy performance assessment does not include latent heat load, which may lead to a structural weakness for a location where energy need for (de)humidification is significant. Although normative model is a best candidate as it is a right engineering approach for the large scale energy performance assessment, the current CEN-ISO calculation method may need to be recalibrated in every climate with local building types and technologies.

2.2.2 Performance Indicators

The three levels of energy performance analysis in the normative calculation results support different strategies. The analysis provides information at distinct levels:

- Level 1: the total expected thermal energy demand of the building (Q_{nd});
    - Used to rate and certify the envelope and internal energy use in the building.
- Level 2: the total expected delivered energy to the building (E_{del}), Heating (E_{heat}), Cooling (E_{cool}), Lighting (E_{light}), Fan (E_{fan}), Pump (E_{pump}), DHW (E_{dhw}), Other Service (E_{os}) ;
    - Used to rate and certify the building systems dealing with HVAC systems including but not limited to district cooling, DHW, lighting controls, auxiliary equipment, on-site renewable energy systems and strategies.
- Level 3: the total expected contribution of the building to primary resource (E_p) and CO_2 emissions
    - Used to rate and certify the building as consumer of all primary energy resources, specifically fossil fuels, and direct and indirect production of CO_2 emissions. This level takes into account the total energy generation and transport topology from power plant to building site.

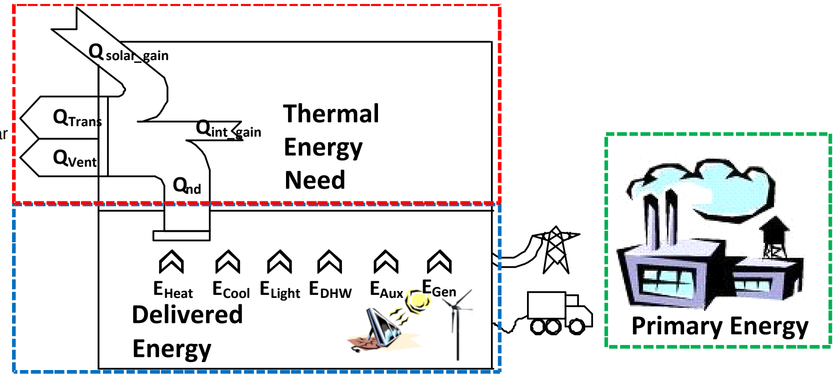
The calculation methodologies are based on various energy standards and supporting documents produced by the CEN and ISO, and the calculation can be grouped according to the procedure of performance-based assessment. Calculation starts from level 1: thermal energy needs (Q_{nd}) which take into account the energy losses (transmission and ventilation), the heat gains (solar, internal and system heat sources), and the dynamic parameters (gain and loss utilization factor). On level 2: delivered energy (E_{del}), the required energy for heating, cooling, ventilation, domestic hot water, lighting, and auxiliary system is calculated. It is necessary to first calculate thermal energy needs for heating and cooling systems. Each system energy requirement is calculated based on the designed system. Heating and cooling energy losses via water or air delivery, renewable energy generation on site have all been taken into account. The resulting estimate of delivered energy corresponds to the total annual delivery of each energy carrier. On level 3: primary energy (E_p) and CO_2 emission is calculated on the basis of the calculated delivered energy and weighting factors (primary energy factor and CO_2 emission coefficient). Figure 4 depicts the major features that are taken into account in the building energy performance calculation.

[Level1] Thermal Energy Need

- Performance evaluation of thermal energy needs

- Includes heat transmission, ventilation, solar heat gain, internal heat gain

- Heating and cooling need: EN ISO 13790
- Ventilation: EN 15241, EN 15242, and EN ISO 13789



[Level2] Delivered Energy

- Performance evaluation of building energy consumption for heating, cooling, lighting, DHW, appliances, auxiliary systems

- Consideration of all on site energy consuming and generating systems

- Heating : EN 15316-1, EN 15316-2, EN 15316-4 series
- Cooling : EN 15243 and NEN 2916
- Lighting : EN 15193
- Fan and Pump : NEN 2916
- Domestic hot water : 15316-3 series
- Generation and Renewables : EN 15316-4-6

[Level3] Primary Energy, CO_2 Emissions

Primary Energy:
Performance evaluation of primary energy use at the source, considering the characteristics of the overall energy supply network, losses, and generations

CO2 Emissions:
Performance evaluation of CO2 emissions to meet building energy requirement from the primary source to delivery

- EN 15603

Figure 4 Building Energy Performance Analysis Process

CHAPTER 3

LARGE-SCALE ENERGY SUPPLY

Building energy performance assessment is useful for understanding how much energy is required by a building. However, when a scale of energy performance is beyond a building such as campus or portfolio, an integrative assessment model which reflects energy supply topology is required to cover an extended scale. This chapter introduces energy supplies linked to buildings and discusses how they are related to the energy performance assessment in the extended scale.

3.1 Energy Grid

The heating, cooling, and electricity needs of the majority of buildings are linked to a grid system. Most buildings rely on energy delivered from central power plants to meet a significant portion of their energy requirements. Reducing the load on centralized conventional power plants that rely on fossil fuels and transport over transmission lines deserves very close attention (NETL, 2007). Figure 5 illustrates a schematic diagram of conventional energy grid.

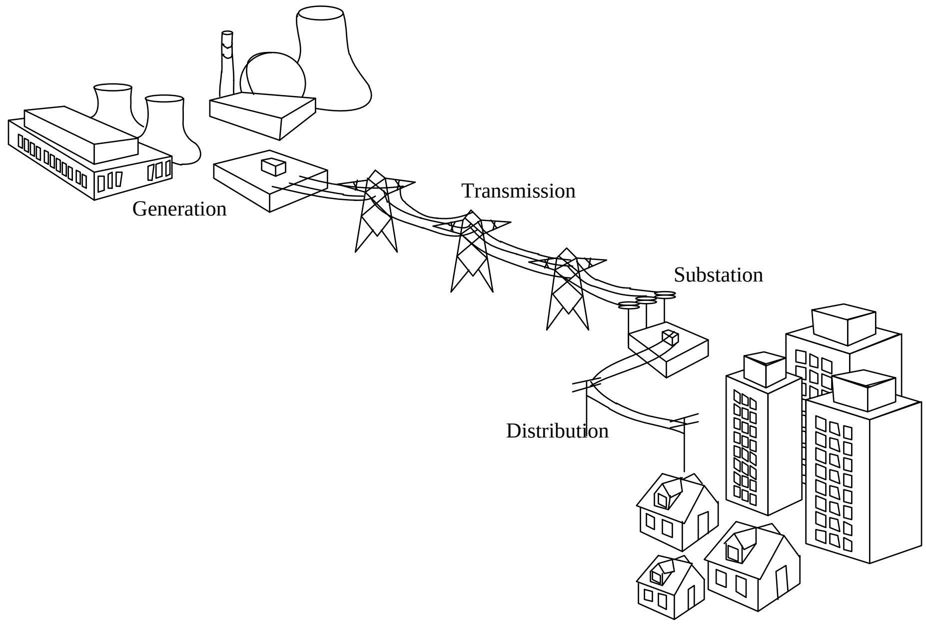


Figure 5 Schematic Energy Flow in Conventional Grid

In the energy grid level, energy efficiency is associated with how energy is produced and distributed. Electric power system comes to the fore in the energy grid because electricity consumed in the building sector accounts for the largest share of the fossil fuel burned in power plants. Major parts of electric power system are generation, transmission, and distribution. The electrical energy generation efficiency varies with the source energy and technology used. Generated electric energy is moved to end-uses through transmission (bulk transfer of electrical energy from generating power plants to electrical substation), and distribution (the process of delivering electrical energy from the high voltage substation to end-users).

The emissions and generation resources integrated database (eGRID) is a globally recognized source of emissions data for the electric power generated in the United States (EPA, 2010). The report provides gross power grid loss factors for the group of states. Figure 6 illustrates the energy grid map for the group of states from North American Electric Reliability Corporation (NERC). is the loss factors which are derived from:

$$\text{Loss Factor} = 1 - \frac{Total\ Consumption}{Net\ Generation + Net\ Imports}$$

.

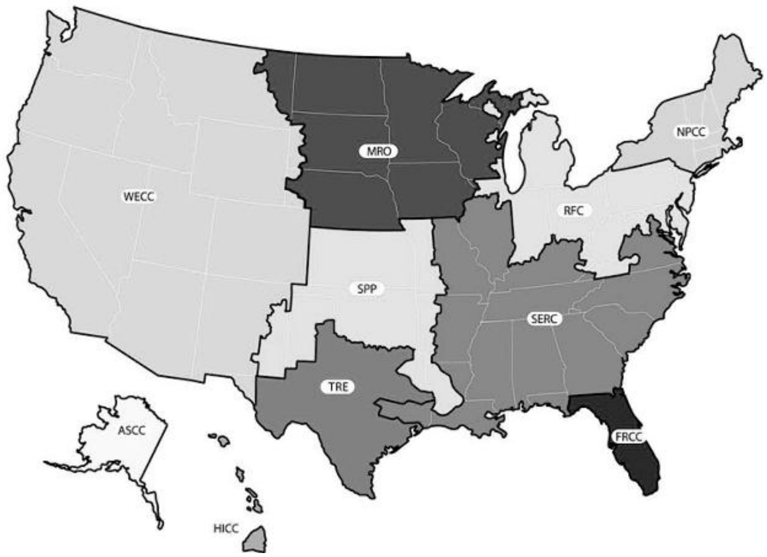


Figure 6 NERC eGRID NERC Grid Map

Eastern Grid:

Florida Reliability Coordinating Council (FRCC),

Midwest Reliability Organization (MRO),

Northeast Power Coordinating Council (NPCC),

Reliability First Corporation (RFC),

South eGrid Reliability Corporation (SERC),

Southwest Power Pool (SPP)

Western Grid: Western Electricity Coordinating Council (WECC)

Texas: Texas Regional Entity (TRE)

Alaska: Alaska Systems Coordinating Council (ASCC)

Hawaii: Hawaiian Islands Coordinating Council (HICC)

Table 1 eGRID Gross Grid Loss Factor Year 2007

Grid (Group of States)	Gross Grid Loss Factor (%)
Eastern Grid	6.471
Western Grid	4.837
Texas	6.415
Alaska	1.244
Hawaii	3.204
U.S.	6.156

A trend is developing that large central power plants are substituted by smaller distributed energy generation, which means that energy conversion units are situated close to energy consumers. This gets more attention when planning involves many buildings such as campus integrating energy generation system for the local energy grid level. Distributed energy supply systems have benefits in (Alanne & Saari, 2006):

- Flexibility: to adapt a variety of energy efficient conversion or renewable technologies
- Networking: to have interaction between supply and consumer to manage energy consumption
- Locality: to utilize local resources

Key items in these integrated systems are distributed energy generation utilizing either renewable sources or waste heat from electricity generation and steam and chilled water distribution from a district heating and cooling network to provide thermal energy.

Figure 7 represents a schematic of an energy grid that includes decentralized energy supply systems linked to buildings.

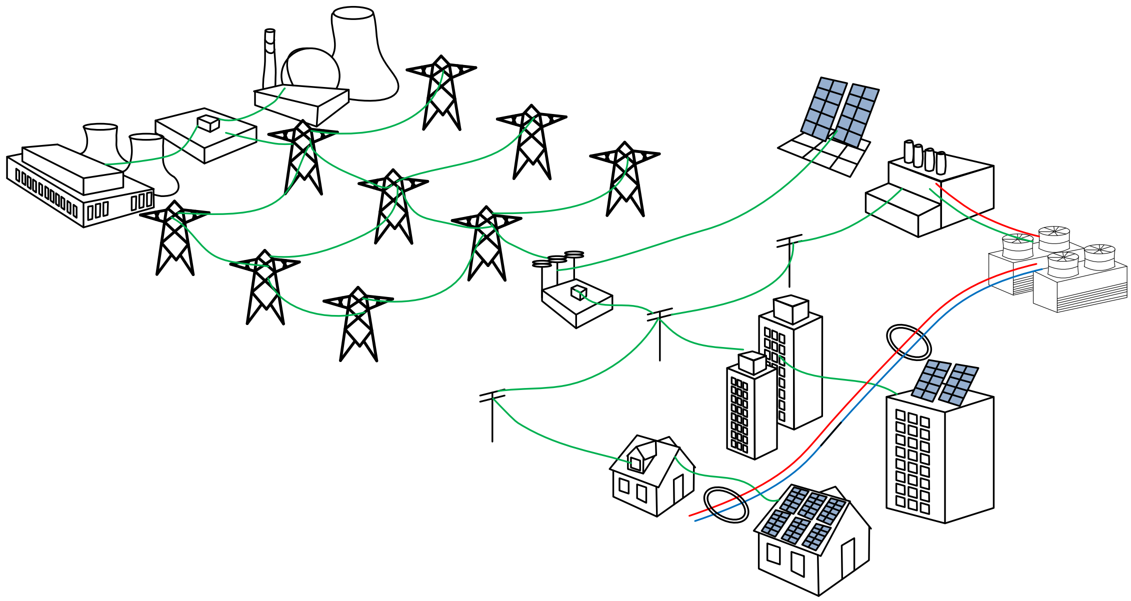


Figure 7 Schematic Energy Flow with Decentralized Energy Supply Systems

The move to an energy efficient grid at the approximate scale of a campus will transform the energy management model for all stakeholders involving utilities, energy service providers, technology vendors, and all consumers (Litos Strategic Communication, 2008). The integrating energy supply systems at various scales has placed emphasis on energy saving strategies that will make changes in the way power is delivered, consumed, and priced. In conjunction with energy efficient supplies, intelligent two-way information flows between the energy suppliers and customers will deliver real-time information and enable balanced supply and demand at the building and large-scale level. The distributed energy supply system will increase reliability and distribution efficiency and improve responsiveness, which can manage energy generation and storage capacity for both the providers and customers. However, energy distributing infrastructure is scattered with a variety of small and large supply sources, which places increasing importance on load management and energy storage to share intermittently generated power in the system (Battaglinia, Lilliestamb, Haasb, & Pattc, 2009). The deployment of such an energy efficient grid system is recognized as an important factor in reducing emissions, since electricity is the most significant source of GHG emissions (Leeds, 2009).

3.2 Primary Energy and Emission Evaluation

Primary energy factors and CO_2 emission coefficients are used to estimate the impact of primary energy consumption and CO_2 emission from the energy delivered to the building sector. The primary energy factors are derived from the ratios of primary resource inputs at the power plants to electricity or fuel delivered. CO_2 emission coefficients are derived for the same purpose to account for the CO_2 emissions resulting from the primary resource inputs at power plants (EPA, 2009). The performance assessment of power plants leads to the primary energy factor, which is used to estimate the primary energy consumed at the power plant, and CO_2 emission coefficient that is used to estimate CO_2 content emitted during fuel combustion at the power plant. The primary energy factors and CO_2 emission coefficients vary depending on the type of resources used for electricity generation at power plants and the type of delivered energy as secondary energy from power plants.

Primary energy factors and emission coefficients represent the combination of conversion inefficiencies at the power plant and the transmission and distribution losses from the generation sources to the point of use. The conversion inefficiencies include the pre-combustion effects, which are associated with extracting, processing, and delivering the primary resources to the point of conversion in the power plant or directly in the buildings. National Renewable Energy Laboratory (NREL) published data for primary energy factors and emission coefficients for the group of states in the NERC grid (Deru & Torcellini, 2007).

Table 3 CO2 Equivalent Emission Coefficient for Delivered Electricity shows primary energy factors for delivered electricity, and indicates emission factors for CO_{2e} (equivalent carbon dioxide) of a compound of the CO_2 which is used to measure a global warming potential from electricity use in buildings.

Table 2 Primary Energy Factor for Delivered Electricity

Unit: kWh/kWh	National	Eastern	Western	ERCOT	Alaska	Hawaii
Total Fossil Fuel	2.500	2.528	2.074	3.168	3.368	3.611
Total Nonrenewable Energy	3.188	3.321	2.415	3.630	3.386	3.653
Renewable Energy	0.177	0.122	0.48	0.029	0.264	0.368
Total Energy	3.365	3.443	2.894	3.658	3.650	4.022

Table 3 CO2 Equivalent Emission Coefficient for Delivered Electricity

Unit: g/kWh	National	Eastern	Western	ERCOT	Alaska	Hawaii
CO_2e	758	788	594	834	774	865

3.3 Energy Generation

The world's energy demand is expected to increase 60 percent by 2030 (IEA, 2004). Because of the challenges posed by the surge in energy use, the fossil-based energy system of today needs to see a dramatic transformation to prevent dangerous climate change. Power plants relying on fossil energy resources were developed during a time of low and constant energy prices and before the climate crisis became apparent. For example, the U.S. relies on coal for over half of its total energy requirement, but coal emits a significant amount of CO_2. Consequently, changes in electricity generation system have a significant impact on CO_2 emissions (EPA, 2009). Global leaders agreed on a long-term goal of reducing emissions by at least 50 percent by 2050, an 80% or more reduction goal for developed countries by 2050 in the G8 summit of 2009 in the city of L'Aquila (G8 Summit, 2009). In order to combat climate change, massive replacement and localization in the energy supply infrastructure will be required to replace much of the world's current infrastructure for fossil energy resources.

A variety of technology options are available to mitigate emissions from the electricity system in the coming decades. Among the most discussed at the moment are carbon capture and storage, nuclear power, and an increasing variety of renewable energy sources such as wind, solar, biomass, ocean waves, hydro and geothermal power. Coal plants dominate current power generation, and research has focused on carbon capture and storage (CCS) technology for cleaner coal power. Despite that, at least until 2020, no significant deployment of CCS can be expected. Also, it seems unrealistic that the nuclear sector can be expanded quickly or on a large enough scale to contribute significantly to climate change mitigation (Battaglinia et al., 2009). Furthermore, nuclear remains highly controversial and due to the inherent technological, weapons-related, and political risks, so it should be considered very cautiously in the debate. As an alternative, renewable energy resources offer clean alternatives to fossil fuels. They produce little or no pollution or greenhouse gases, are widely available and never run out. Therefore, one of the key objectives of worldwide energy policy is a substantial increase in the use of renewable energy sources, coupled with a massive increase in energy efficiency. . For electricity generation and distribution, renewable energy resources offer clean alternatives to fossil fuels. It is expected that generation by renewable technologies will become the second-largest source of electricity after 2010, following coal (IEA, 2008).

Energy generation from renewable sources can be either on-site or at grid-scale. The renewable sources are, for example, sun, wind, or biomass. This research focuses on electricity generation from the sun using photovoltaic (PV) systems. Energy generation from PV plants is currently growing at a 40 percent per year rate (Rosa, 2009). The current NEP model includes the energy generation from PV power stations at the district level as well as PV systems attached to or adjacent to individual buildings or groups of buildings.

3.3.1 PV Renewable Energy

Semiconductor solar cells are the core technologies which determine the generation efficiency for photovoltaic systems. The efficiency of typical silicon-based solar modules is around 13-14 percent, and the currently available advanced technology, which uses crystalline solar cells, can reach to 24 percent (Wenham, Green, Watt, & Corkish, 2007). PV module energy generation efficiencies for different solar module types are presented in , which is for peak power generation. The overall electricity generation is variable and dependent on the climate condition, and rages from 5 percent to 20 percent. The NEP model quantifies energy generation for different solar modules and climate data for the selected location.

Electricity generation from a photovoltaic system is calculated using the calculation method prescribed by the CEN standard EN 15316-4-6:2007 (CEN, 2007c) applying hourly time steps. The standard calculation for electricity generation from a PV system is as follows:

$$E_{el,pv,out} = \frac{E_{sol,hor} \times f_{tilt} \times K_{pk} \times A \times f_{perf}}{I_{ref}}$$

where

$E_{el,pv,out}$ is the electricity produced by the PV system, in kW;

f_{perf}	is the system ventilation performance factor for building integration with PV module (unventilated 0.7, moderately ventilated 0.75, strongly ventilated 0.8) ;
I_{ref}	is the reference solar irradiance equal to 1 kW/m^2;
$E_{sol,hor}$	is the hourly solar irradiance on a horizontal surface, in kW/m^2;
f_{tlt}	is the PV module tilt and orientation conversion factor;
K_{pk}	is the PV module peak power coefficient for a given surface for a solar irradiance of 1 kW/m^2 at 25 °C, in kW/m^2;
A	is the total surface area of all PV modules, in m^2.

Table 4 PV Panel Peak Power Coefficient

Type of PV module	K_{pk} (KW/m^2)
Mono crystalline silicon (at least 80 % density)	0.12 - 0.18
Multi crystalline silicon (at least 80 % density)	0.10 - 0.16
Thin film amorphous silicon	0.04 - 0.08
Other thin film layers	0.035
Thin film copper-indium-gallium-diselenide	0.105
Thin film cadmium-telluride	0.095

3.3.2 Energy Storage

PV plants and on-site PV systems generate electricity only during the day and only when exposed to relatively direct sunlight. Depending on the climate conditions, energy generation may exceed demand during some period of the daytime, and the over generated energy cannot be utilized without a storage system. To store the otherwise wasted over generated energy and to effectively make it useful during periods of no sunshine or partial sunshine and at night, some form of storage system is necessary. This is not initially a big issue if a small number of plants and on-site PV systems are to be integrated within an existing fossil-fueled grid system. However, the issue gains increasing importance as the solar-to-fossil ratio increases. The fluctuating solar input on grid stability will then need to be given more attention in conjunction with the energy storage system (Kurokawa, Komoto, Vleuten, & Faiman, 2007). The primary function of the storage system is to accumulate the excess solar energy generated and to deliver it when required. Batteries are mainly used to store generated energy to ensure energy availability throughout periods of low insolation. There are many types of batteries for use in PV systems. The most commonly used is lead-acid, while nickel-cadmium, nickel-metal-hydride, rechargeable alkaline manganese (RAM), lithium-ion, lithium-polymer and redox-flow batteries are potentially available. Also, other battery system technologies are under development for higher efficiency and longer term storage. The overall energy efficiency of batteries depends on charge efficiency and voltage efficiency, and the energy efficiency of typical lead-acid batteries is 72 percent. Recent DOE sponsored research on energy storage supports a wide variety of storage technologies. Besides batteries, there is also research into the use of flywheels, electrochemical capacitors, superconducting magnetic energy storage, power electronics, and control systems. In addition to decreasing the reliance on fossil fuels, a grid incorporates some energy storage would have other benefits. For example, an energy generation system integrated with a storage system can help regulate the problem-causing fluctuations power line frequency that occurs as the overall load on the grid changes. This would help maintain the balance between the network's load and generation and support a more reliable power supply. Accordingly, renewable energy generation and storage along with a smart gird nourish substantial promise to transform the electric power industry (DOE, 2009; National energy Technology Laboratory, 2009).

3.4 District System

District heating (DH) and district cooling (DC) systems provide thermal energy sources for multiple buildings, and have many advantages. High energy efficiency and inherently less environmental impact, intensive use of chiller and boiler system, inherent savings on operation and maintenance costs, and space utilization on individual buildings have drawn increased attention to DH/DC systems in recent years. Much research has proven that the energy efficiency in DH and DC is superior to individual heating and cooling systems for building because of the "concentration effect" and "grade of operation" (Shimoda, Nagota, Isayama, & Mizuno, 2008).

A large amount of heat is produced during power generation, but waste heat has not been used effectively in conventional power plants. Cogeneration simultaneously produces power and usable heat, and increases energy generation efficiency by 35 percent to 80 percent (DOE, 2000). District energy systems which incorporate cogeneration produce electricity and usable thermal energy in the form of hot water or steam and chilled water. Utilization of the waste heat from boilers or electricity generation processes has been proved more efficient, cleaner, and more cost effective than conventional supply system (Rosen, Le, & Dincer, 2005).

3.4.1 District Heating, District Cooling, Combined Heat Power Performance Assessment

EN 15316-4-5:2007 (CEN, 2007b) outlines the energy balance of district heating system. Based on the approach from the standard, Figure 8 was developed in order to integrate the performance evaluation of district heating and cooling system including CHP.

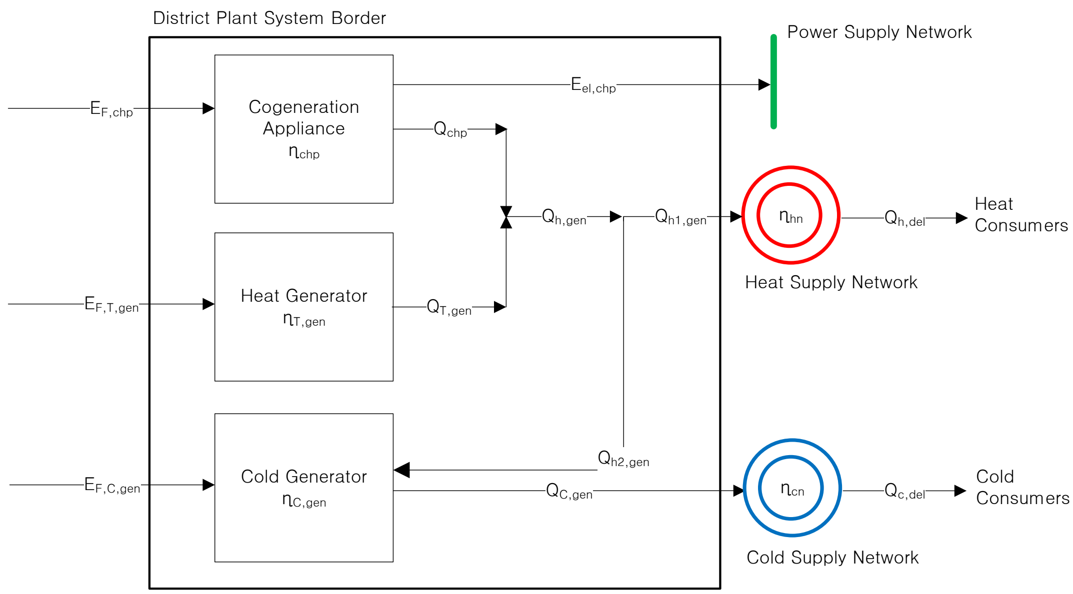


Figure 8 DHC and CHP Energy Balance Diagram

The DHC and CHP system performance assessment is integrated to the NEP model on the basis of the standardized calculations which are introduced below:

Combustion heat generator efficiency: $$\eta_{chp} = \frac{E_{el,chp}+Q_{chp}}{E_{F,chp}}$$

Cogeneration appliance efficiency: $$\eta_{T,gen} = \frac{Q_{T,gen}}{E_{F,T,gen}}$$

Cold generator efficiency: $$\eta_{C,gen} = \frac{Q_{C,gen}}{E_{F,C,gen}+Q_{h,chp}}$$

Heat supply network efficiency: $$\eta_{hn} = \frac{\sum Q_{h,del}}{Q_{h,gen}}$$

Cold supply network efficiency: $\eta_{cn} = \frac{\sum Q_{c,del}}{Q_{c,gen}}$

σ, power to heat ratio of the cogeneration appliance: $\sigma = \frac{E_{el,chp}}{Q_{chp}}$

β, relation of heat produced by the cogeneration to the total heat production:

$$\beta = \frac{Q_{chp}}{Q_{chp} + Q_{T,gen}} = \frac{Q_{chp}}{Q_{h,gen}}$$

For assessment of a district plant system, the primary energy factor for district heating, $f_{p,dh}$ and district cooling, $f_{p,dc}$ is determined by:

The energy balance equation for $f_{p,dh}$:

$$f_{p,dh} \sum Q_{h,del} + f_{p,el} E_{el,chp} = f_{p,chp} E_{F,chp} + f_{p,T,gen} E_{F,T,gen}$$

$$f_{p,dh} = \frac{(1+\sigma)\beta}{\eta_{hn}\eta_{chp}} f_{p,chp} + \frac{1-\beta}{\eta_{hn}\eta_{T,gen}} f_{p,T,gen} - \frac{\sigma\beta}{\eta_{hn}} f_{p,el}$$

The energy balance equation for $f_{p,dc}$:

$$f_{p,dc} = \frac{f_{p,c,gen} E_{F,C,gen} + f_{p,dh} Q_{h2,gen}}{\sum Q_{C,del}}$$

where

$E_{F,T,gen}$ is the fuel consumption of the combustion heat generator during the period of interest (usually one year);

$Q_{T,gen}$ is the heat production of the combustion heat generator measured at the output of the generator during the same period;

$E_{F,chp}$ is the fuel consumption of the cogeneration appliance during the same period;

$E_{el,chp}$ is the power production of the cogeneration appliance during the same period measured at the output of the appliance;

Q_{chp} is the heat production of the cogeneration appliance during the same period measured at the output of the appliance.

Thermal energy loss at a building substation is calculated as following:

$$Q_{dh,gen,ls} = H_{dh,gen}(\theta_{dh,gen} - \theta_{amb})$$

with $H_{dh,gen} = B_{dh,gen}\Phi_{dh,gen}\Phi_{dh,gen}^{1/3}$

and $\theta_{dh,gen} = D_{dh,gen}\theta_{dh,gen,in} + (1 - D_{dh,gen})\,\theta_{dh,gen,out}$

where

$Q_{dh,gen,ls}$ is the system thermal loss of the heat generator (building substation);

$H_{dh,gen}$ is the heat exchange coefficient of the building substation, in kWh/K/yr;

$\theta_{dh,gen}$ is the average temperature of the building substation, in ℃;

θ_{amb} is the ambient temperature at the location of the building substation, in ℃;

$B_{dh,gen}$ is the coefficient depending on the type of building substation, from Table 6 Average Primary Heating Medium Temperature and Coefficient from the Substation Type

;

$\Phi_{dh,gen}$ is the nominal power of the building substation, in KW;

$D_{dh,gen}$ is the coefficient depending on the type of building substation and its control, from ;

$\theta_{dh,gen,in}$	is the average heating medium temperature of the primary (input) circuit of the building substation, in ℃, informative values are given in ;
$\theta_{dh,gen,out}$	is the average heating medium temperature of the secondary (output) circuit of the building substation in ℃.

Table 5 Coefficient $B_{dh,gen}$ as a Function of Insulation Class and Type of Network

Type of Circuit	Insulation Class of the Components of the Dwelling Station (Class specified by prEN ISO 12241)			
Secondary Circuit	4	3	2	1
Primary Circuit	5	4	3	2
Type of Network	Coefficient $B_{dh,gen}$ [-]			
Hot Water, Low Temperature	3.5	4.0	4.4	4.9
Hot Water, High Temperature	3.1	3.5	3.9	4.3
Vapor, Low Pressure	2.8	3.2	3.5	3.9
Vapor, High Pressure	2.6	3.0	3.3	3.7

Table 6 Average Primary Heating Medium Temperature and Coefficient from the Substation Type

Type of Dwelling Station	Average Primary Heating Medium Temperature $\theta_{dh,gen,in}$ (℃)	Coefficient $D_{dh,gen}$
Hot Water, Low Temperature	105	0.6
Hot Water, High Temperature	150	0.4
Vapor, Low Pressure	110	0.5
Vapor, High Pressure	180	0.4

3.5 Virtual utility

Establishment of a smart grid system increases decentralized electricity energy generation from renewable sources and ensures more reliable electricity supply with less environmental impact. This brings in the concept of a virtual utility which can reinforce the value of energy in the grid (Coll-Mayor, Picos, & Garc!ıa-Moreno, 2004). The virtual utility is recognized as a new concept of energy infrastructure integrating distributed energy generation in the energy grid controlled by an energy management system. The virtual utility has benefits which optimize the utilization of energy in a grid, bring energy prices down for customers, and increase the reliability of energy supply. The energy management system in the virtual grid can provide information about real-time energy pricing to customers (National Energy Technology Laboratory, 2007). Also, customers who have renewable energy generation capability can sell excess power to the grid (Wenham et al., 2007). For example, the price of energy during peak periods such as the summer's hottest hours may be five times more expensive than usual, but this can be controlled with a virtual utility and the establishment of a smart grid (Litos Strategic Communication, 2009).

The NEP model developed here will include a virtual utility from energy generation from BIPV. The hourly performance assessment of building energy performance and BIPV energy generation enables calculation of the amount of excess energy. Depending on climate conditions, if energy generation exceeds the requirement during some period of the day, the over generated energy can be utilized as virtual energy for other buildings.

CHAPTER 4

NEP MODEL AND APPLICATION DEVELOPMENT

Many tools have been developed to analyze the energy performance of buildings at different levels of precision, and at different stages and scales. However, a systematic large-scale building energy performance assessment model which can integrate multiple buildings and energy sources and which incorporates a large scale energy performance assessment for the energy grid has not yet been developed.

In this research, the development of an NEP model aims to quantify the energy performance for all indicator levels as explained in Chapter 2. The NEP model analyze energy performance at a campus level; 1. thermal energy demand, 2. delivered energy, and 3. primary energy and CO_2 emissions. More explicitly this enables to analyze thermal energy demand (heating and cooling load) reduction from buildings as consumers, and improvements in delivered energy reducing electricity or fuel energy consumption in campus scale. Either building integrated systems or district level thermal energy generation systems must satisfy total energy demand determined by campus buildings. Reductions in heating and cooling load from buildings reduces delivered electricity or fuel energy whichever a system uses as its power source. This will result in delivered energy savings eventually CO_2 emission reductions.

The NEP model analyze the energy performance of a large building portfolio systematically including the energy consumption of buildings and energy supplies from various sources including conventional power plants, combined heat and power plant (CHP) electricity from PV stations, potential electricity from building-integrated PV (BIPV) systems as well as thermal energy, such as heat from district heating plants (DHP), cooling from district cooling plant (DCP), and both from CHP.

The discussion in the research focuses on how addition of new supply nodes or rerouting of certain relationships will decrease the delivered energy. The case study in Chapter 5 does not focus on retrofit scenarios in heating and cooling load reductions from buildings (consumers), but shows different retrofit technology options in campus district level suppliers. The model with the NEP software quantifies the energy performance at a district level which the assessment deals with campus wide dynamic retrofit options. The quantification provides rich information for energy managers when they estimate how much energy savings are expected with a certain retrofit system design.

The NEP model consists of several separate modules for software development as illustrated in Figure 9. Each module is further explained in the following sub-sections.

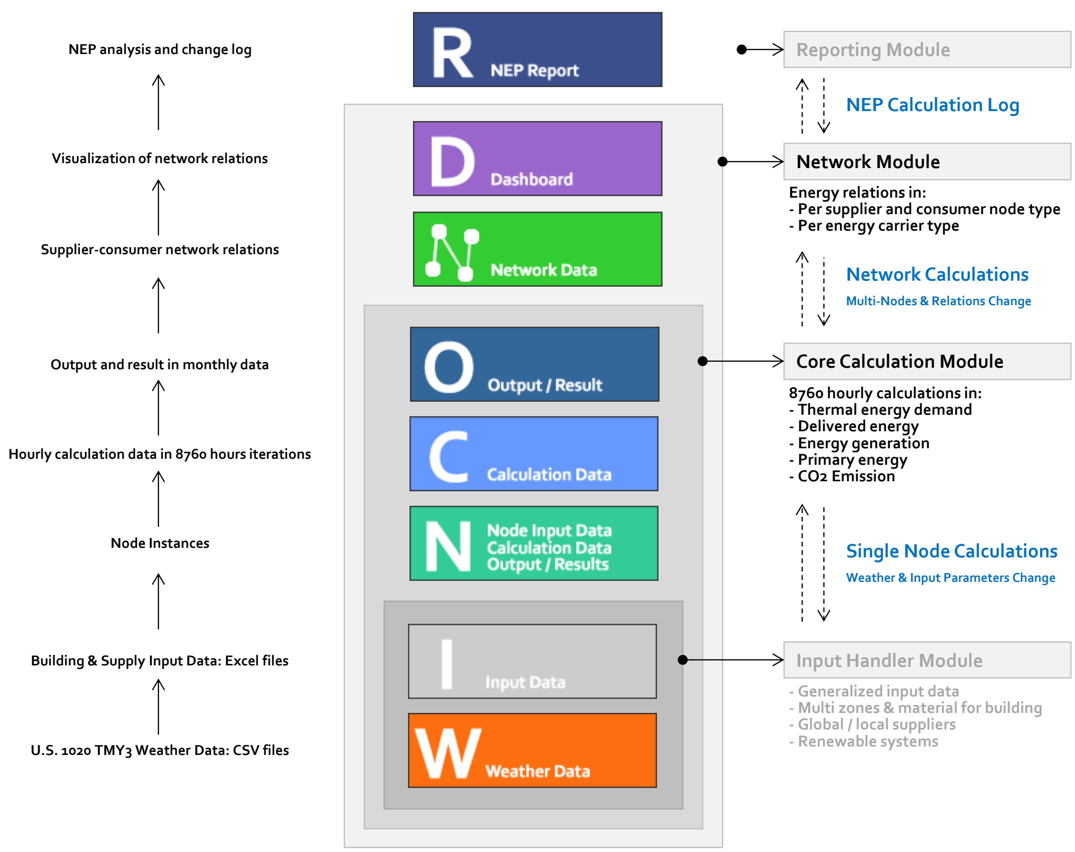
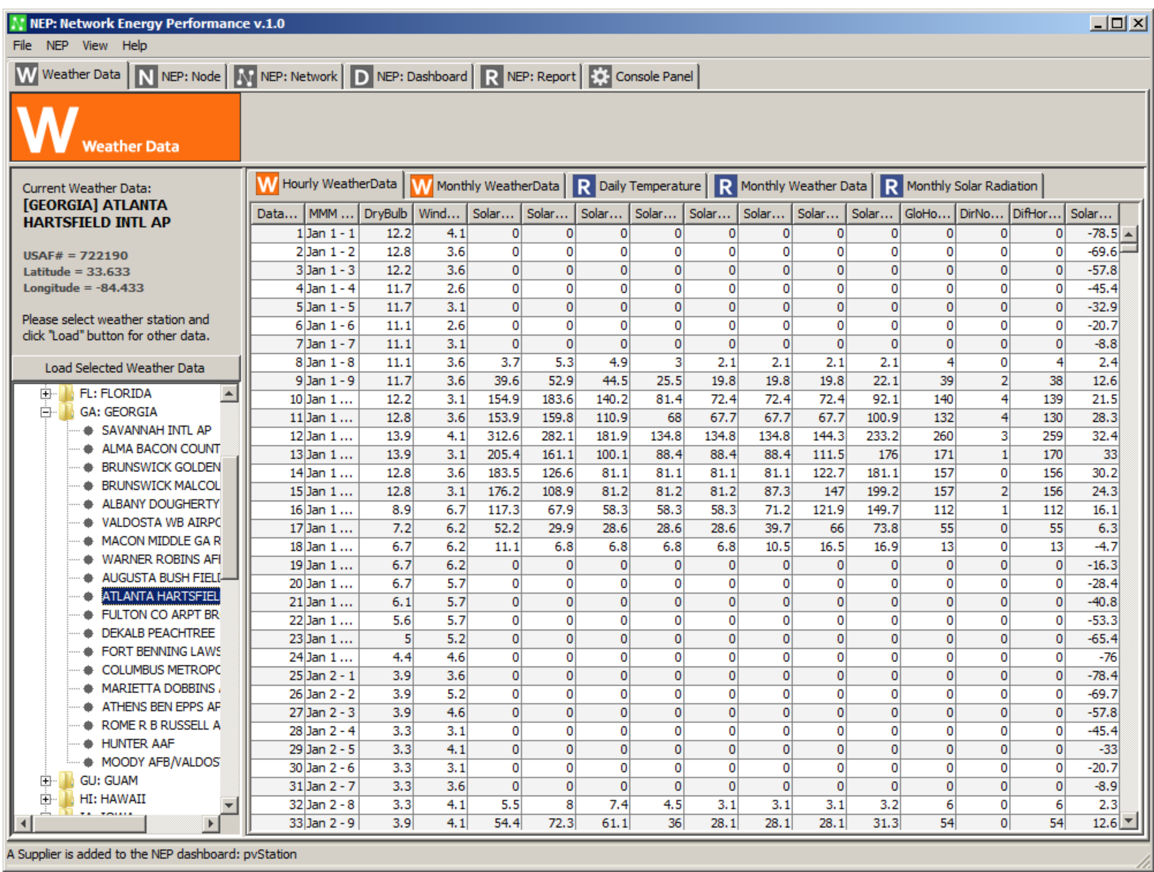


Figure 9 NEP model structure

4.1 Input Handling Module

The input handling module consists of weather data and network node input management panels. The weather data management module provides hourly climate data; dry bulb temperature, solar radiation for global horizontal, direct normal and vertical in eight different orientations, wind speed, and solar altitude, which are required for the core calculation module. The current version supports data input from any of 1,020 U.S. stations found in the TMY3 database. The default weather station setting is for Atlanta Hartsfield-Jackson International Airport, and Figure 10 shows an example of hourly weather data and graphical visualization in a chart for the station.



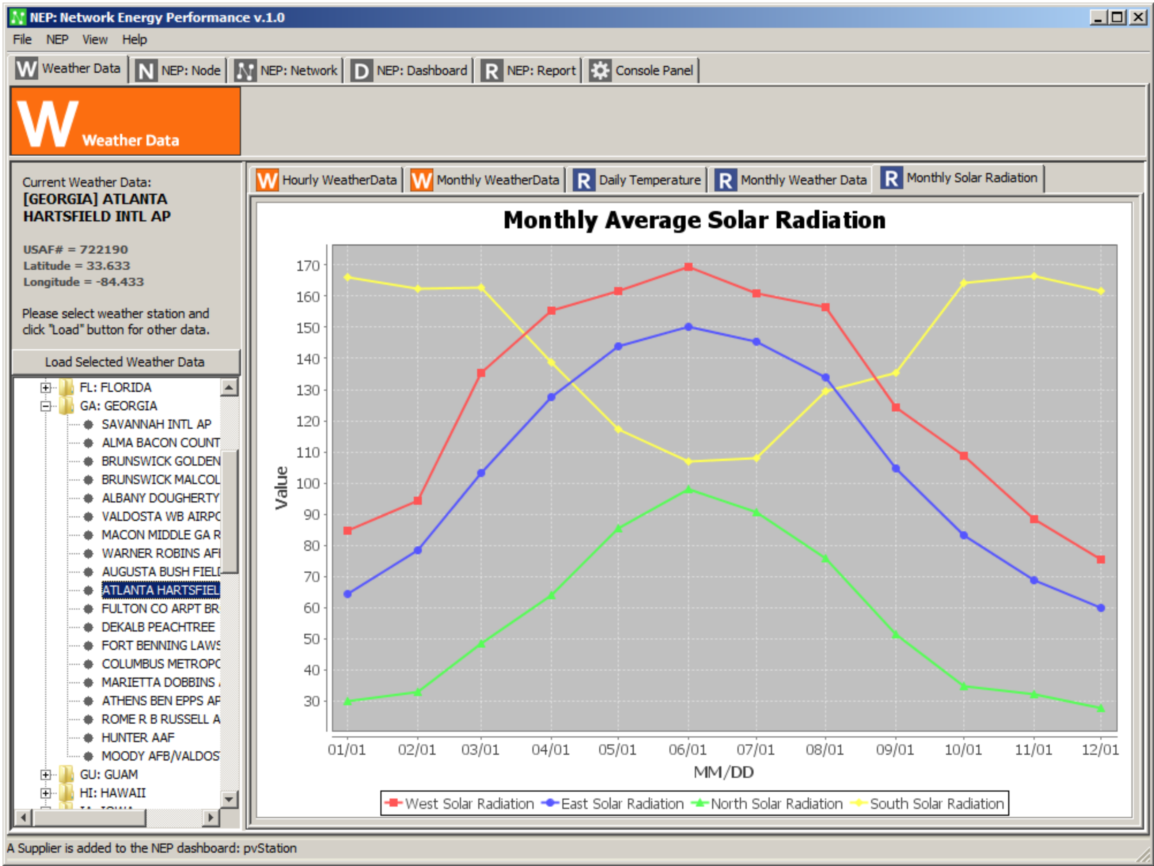


Figure 10 NEP Weather Data Example

The node input data management takes care of adding and removing multiple consumer and supplier nodes which comprise the network energy grid. Required inputs for each node, including consumers and suppliers, are found in Appendix A. The current version requires a completed input template ready for the NEP model.

The building node inputs are intended to be recalculated hourly, which requires hourly schedule data for 8,760 hours of thermal energy demand, energy usage for each consumer, energy generation and energy export. The input template is flexible enough to cover multiple materials for roofing, opaque walls, and glazing, and has zones for different schedules and activities, and energy sectors. The current version includes supplier nodes for power plants at a global scale and district heating and cooling plants, combined heat and power plant, and photovoltaic station at a local scale. Figure 11 shows an example of building node input data loaded in the NEP application.

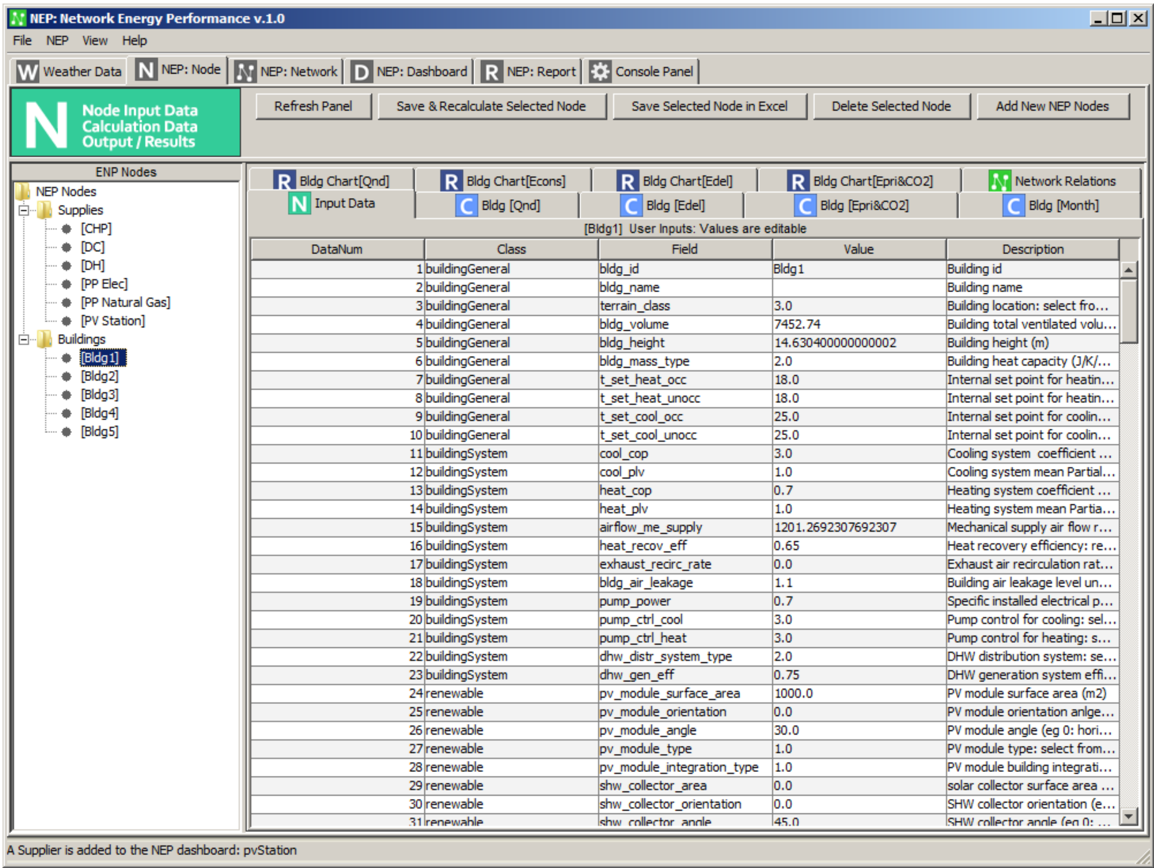


Figure 11 NEP Building Node Data Example

4.2 Calculation Module

The calculation module is the core of the NEP model. The model quantifies the hourly energy performance of each node as well as the network before and after each node is related to the other nodes. Thermal energy needs and energy consumption for each building node are calculated from embedded EPSCT taking into consideration node type, design features, the type of occupants and installed systems. The calculation module also quantifies the amount of generated and exported energy for the installed PV station and BIPV system and the delivered thermal energy from local suppliers. The hourly calculation from the NEP model supports the analysis of the assessment of peak building energy demand and solar energy generation from PV systems.

4.2.1 Building Energy Performance Calculation

The NEP model uses an existing EPSCT calculator based on an equivalent resistance-capacitance (R-C) model discussed in Chapter 2. For the building (consumer) node, the calculation method is based on the CEN/ISO standards and supporting documents. When the NEP loads building nodes, The EPSCT is called, and calculates the building level energy performance, which includes heating and cooling demand and energy usage for each energy consuming system.

4.2.2 PV Electricity Generation Calculation

For the purpose of demonstration, the scope of the energy generation calculation is limited to PV electricity generation even though it is recognized that there are many other renewable sources of energy generation. The calculation method was discussed in the previous chapter regarding solar energy generation from PV station or BIPV systems. The calculation is focused on the electricity generation from PV systems based on the specifications of solar modules and hourly climate data from Typical Meteorological Year 3 (TMY3). PV energy generation takes place during daytime, so the generated energy is used to meet building energy requirements during daylight hours. The excess is stored in the battery system to be used when sunlight is not available, or it can act as a generator to deliver electricity energy to other buildings.

4.2.3 Delivered Thermal Energy Calculation

Buildings which are connected to the district heating or cooling plant typically use hot water or steam for heating and chilled water for cooling. The amount of delivered thermal energy is determined by the building's cooling and heating energy demand. Overall DHP or DCP system efficiencies are to be determined based on the system types such as boilers or chillers in conjunction with CHP. The model quantifies both the delivered thermal energy from DHP or DCP to buildings and its effects in reducing the energy demand and the environmental impact of emissions. The NEP model provides hourly outcomes of delivered energy consumption, thus enabling the analysis of peak demand and strategies to mitigate the power load to the entire network.

The NEP model provides calculated outputs for each of the following:

- Building node
    - Thermal energy needs
        - Heating and cooling needs
        - Internal heat gain (occupants, appliances, lighting) and solar heat gain
        - Heat transfer by transmission (via roof, opaque wall, and glazing), and ventilation (infiltration, mechanical, natural, and hybrid)
        - DHW needs
        - Internal temperature

    - Energy usage
        - Heating, cooling, lighting, fan, pump, DHW, equipment
    - Energy generation and export
    - Delivered energy
        - Electricity from other buildings, PV station, CHP plant
        - Total delivered energy by energy carrier
    - Primary energy and CO_2 emission by each carrier for the delivered energy to the building
- Local Supplier node : DCP, DHP, and CHP
    - Thermal energy needs
        - Heating, cooling, and DHW needs for connected buildings
    - Energy usage for local suppliers
        - Energy used for heat and cold production for connected buildings
    - Electricity generation by the CHP
        - Electricity generation from the cogeneration process
    - Electricity supported by PV station for DC
    - Primary energy and CO_2 emission by each carrier for the delivered energy to the local supplier
- PV station node
    - Electricity generation
    - Electricity required by connected buildings and DC
    - Electricity delivered to buildings and DC
    - Electricity available to store
- Global supplier node : Electricity Power Plant and Fuel Plant
    - Delivered electricity or fuel energy by power plants to buildings and local suppliers

- Primary energy and CO_2 emission from electricity or fuel used by buildings and local suppliers

Figure 12shows an example of the thermal energy need output table from an hourly calculation, and Figure 13 illustrates an example of the chart that presents calculation results in a monthly format.

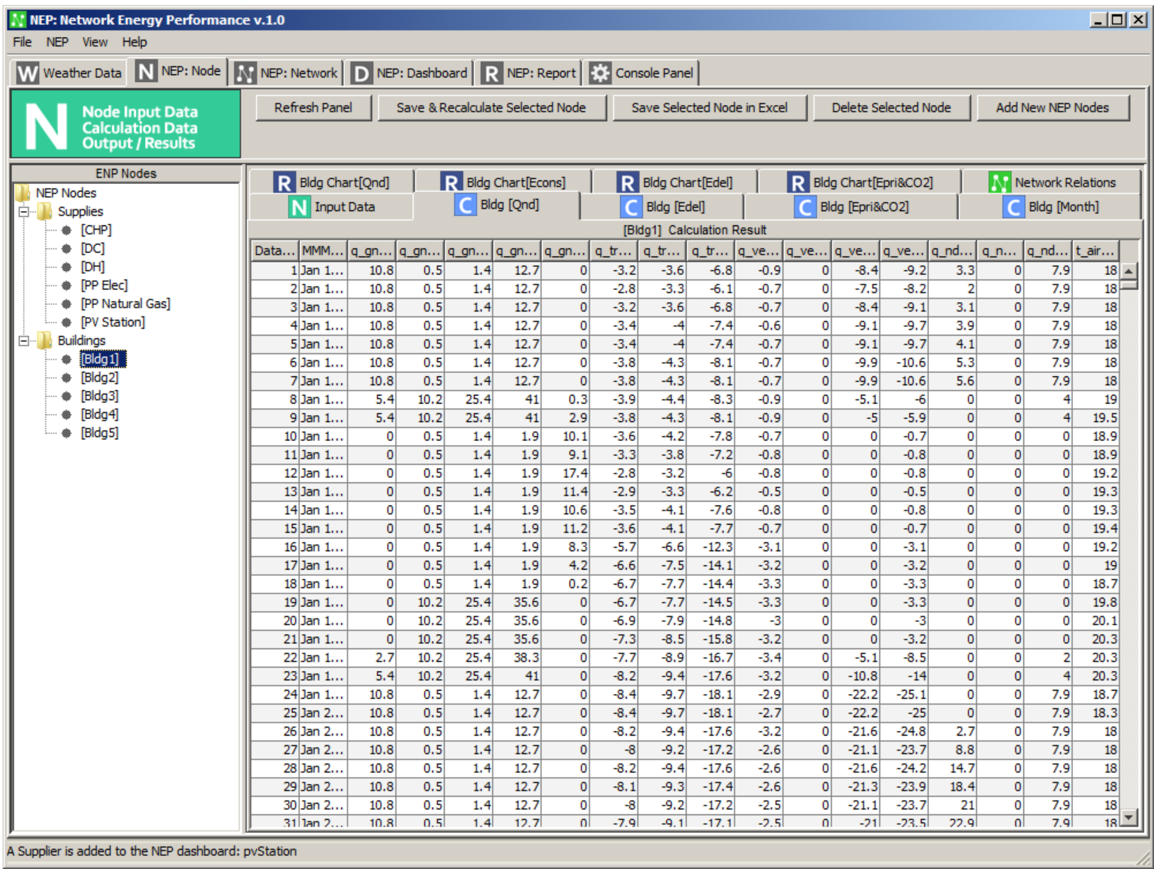


Figure 12 NEP Building Node Thermal Demand Hourly Calculation Output Table Example

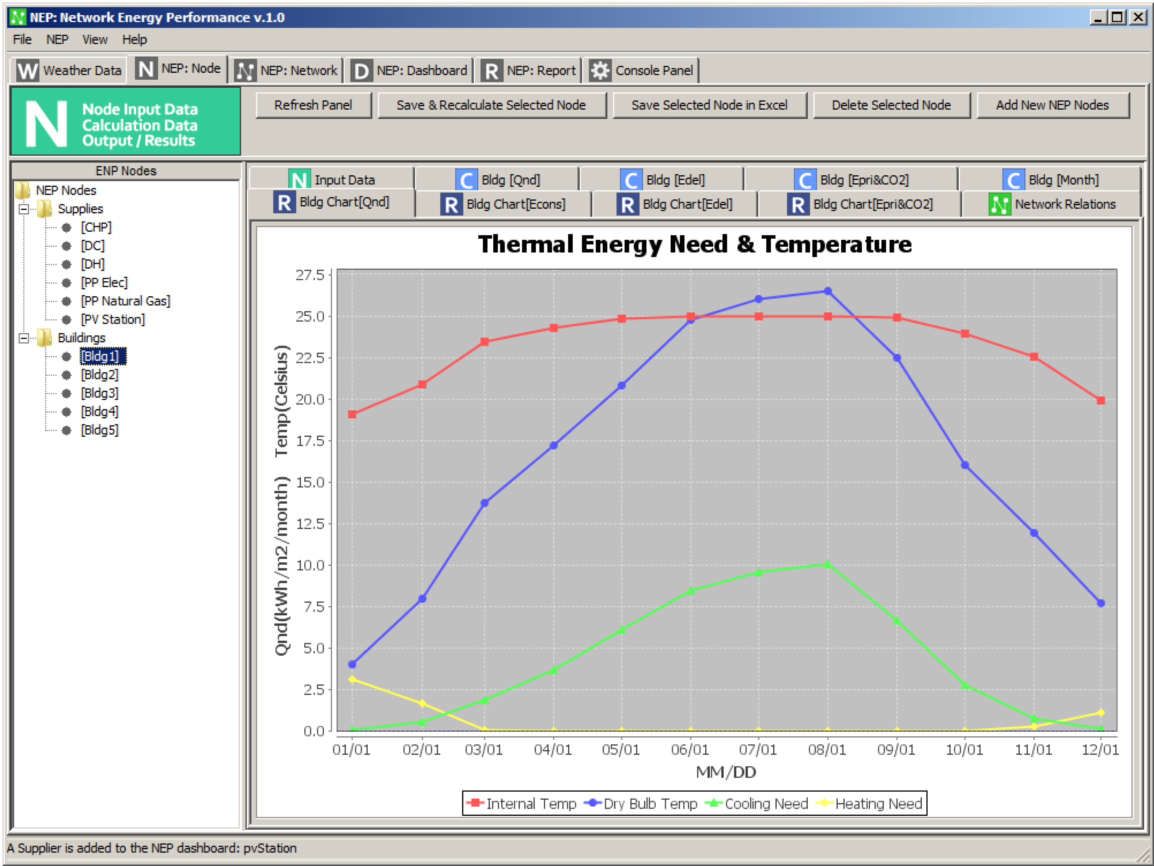


Figure 13 NEP Building Node Thermal Demand Calculation Output Monthly Chart Example

4.3 Network Module

The NEP model enables effective energy performance analysis on a large scale (campus or portfolio scale), typically consisting of multiple buildings and local thermal energy suppliers. The network module aims to manage the energy flow relations between nodes through the interface both in a high-level graphical dashboard and low-level network panel. The dashboard panel helps to provide an overview of network energy flows through graphical visualization. The module supports the agile management of the different kinds of network energy flow between suppliers and consumers, and filters irrelevant energy flows out. The relations are constructed based on directed arcs, a technique taken from graph theory, discussed below.

4.3.1 Graph theory

Graph representations serve effectively as mathematical models to analyze numerous real-world problems (Balakrishnan & Ranganathan, 1999). Graphs are simple diagrams consisting of points (vertices or nodes) and lines (edges). Graphs are used extensively to represent the form or diagrammatic model of a system. They are simplified abstractions of reality and are useful in enhancing the understanding of complex systems and phenomena.

An undirected graph refers to a graph in which there is no distinction between the two vertices associated with each edge. The directed graph, by contrast, has edges that are directed from one vertex to another. Directed edges are called arcs. Representing energy flow graphically requires the specification of a direction of flow, and all thus dictates the need for arcs. A directed graph is represented by $G(V, A)$ where A is the set of arcs $(a_1, a_2, a_3 \dots a_n)$. The arc, $a_1 = (v_1, v_2)$ is used to represent an arc originating at vertex, v_1 and ending at vertex, v_2. The vertex, v_1 is a positive incident, while v_2 is a negative incident. These are denoted by $\mathrm{pos}\, d(v_1)$ and $\mathrm{neg}\,(v_2)$, and the relationship between the nodes of a directed graph is as follows:

$$d(v) = \mathrm{pos}\, d(v) + \mathrm{neg}\, d(v), \text{for all } v \in V$$

It is important to deal with flows from one vertex of the network to another in a physical network. The NEP model dashboard is represented as a network flow graph model as shown in Figure 14 as P1 and P2 denoting suppliers, C1 and C3 consumers, and C2 both supplier and consumer.

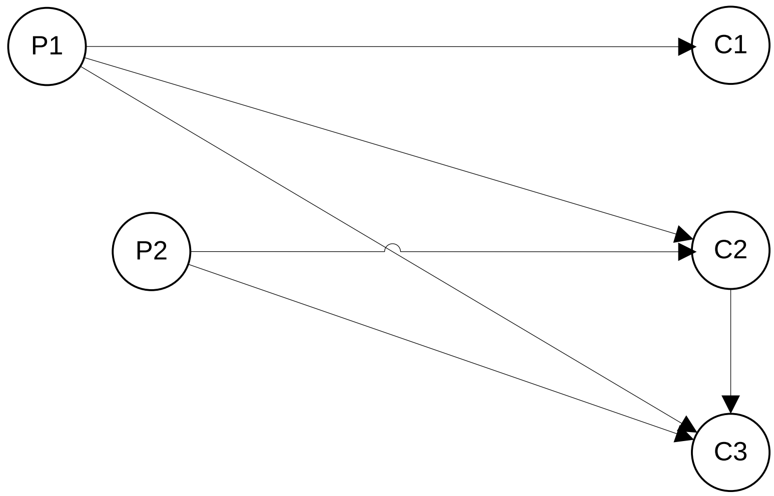


Figure 14 Directed Graph Network Model Network

The major components of the NEP model are nodes and arcs. A node represents an energy consumer or producer connected to the energy arc(s). In this simple example, the energy flows are stated as following: Let p_1, p_2, p_3 ... p_n be n energy suppliers which distribute energy to m consumers, c_1, c_2, c_3 ... c_m. The amount of energy demand at a consumer node is already determined by the consumer when a node is added to the NEP model. Buildings represent energy consumers where the energy performance of each consumer is assessed with the hourly calculation method from the EPSCT. It is assumed that the global and local suppliers always meet the energy requirement by consumers. Producers represent various electrical power and thermal energy suppliers which have a unique primary energy factor (PEF) and CO_2 emission coefficient determined by their system efficiencies and technologies.

The sum of the energy supplied to consumers to meet total energy requirements (from supplier, p_i to consumer, c_j) is used to estimate the environmental impact of CO_2 .emissions from power plants. The objective of the network module is to enable the design of energy flows with different energy carriers in the energy grid. The network directed arcs for different energy carriers are linked to the parameters in the core energy performance calculation, which quantifies the total primary energy used and CO_2 gases emitted.

4.3.2 Energy Flow Connection

In the microcosm of the grid at a campus scale, energy flows from supplier nodes to consumer nodes entail various connections, a subset of which is supported by the NEP model. The connections between suppliers and consumers are determined whether an energy carrier such as electricity, fuel energy or thermal energy; steam or chilled water is the energy source for a system at a consumer level. The supported connections in the current NEP model are illustrated in

Figure 15. The left node denotes a supplier, and the right node a consumer. The arc (connection), showing the energy carrier and consumer type is located between the two nodes.

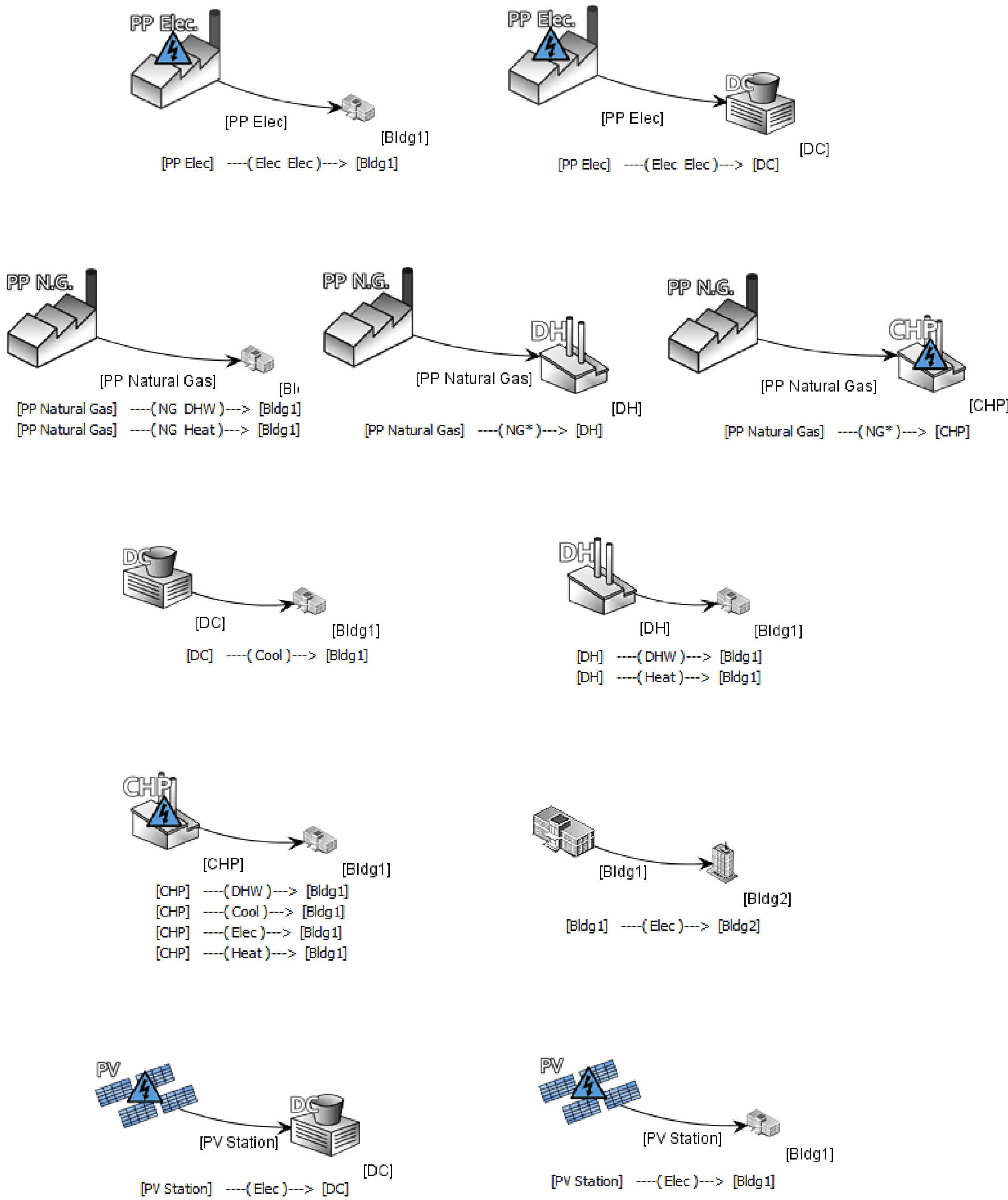


Figure 15 Network Energy Flow Scenarios in Network Module

Supplier Node:

- PP Elec: conventional power plant distributing electricity to the network.
- PP NG: Natural gas utility delivering fuel energy

- DH (a supplier): district heating plant in a local energy network distributing heat (steam or hot water)
- DC (a supplier): district cooling plant in a local energy network distributing cold (chilled water)
- CHP (a supplier): a combined heat and power plant in a local energy network distributing thermal energy as well as generating electricity, thermal energy includes heat as well as if the system has absorption chillers
  - Cogeneration: generating heat and electricity
  - Trigeneration: generating heat, cold, and electricity
- PV: PV station in a district level generating electricity for a electricity network
- Bldg (a supplier): BIPV exporting excess electricity to other buildings

Consumer Node:

- Bldg: a building connected to supplier node(s) for energy delivery such as electricity, fuel gas, or thermal energy
- DH: a district heating plant connected to the fuel energy delivery
- DC: a district cooling plant connected to the electricity grid
- CHP: a combined heat and power connected to the fuel energy delivery

Energy Flow:

- Energy carrier: electricity, fuel gas, heat (steam or hot water), cooling (chilled water)
- Consumer type: electricity, heat, cooling, DHW at a building level which may require a different energy carrier for the system operation.

The current version covers energy flows of electricity from power plants and fuel energy delivery as well as a district level energy generation of electricity and thermal energy from local supply systems.

For electricity connections, a CHP represents electricity generation from the heat generation process, and a PV station represents a district electricity generation node that distributes generated electricity to campus buildings or district cooling plant, and a BIPV represents a building scale electricity generation which is capable to export a surplus power to the network. These reduce delivered electricity from a power grid. The connections also support the concept of the virtual energy to export the excess energy from a PV station at a district level or BIPV systems to other electricity consumers. If a PV station generates electricity greater than the demand at a campus level for certain hours, a campus management has options to store or export to a power grid. If a BIPV system at a certain building generates electricity greater than the demand for certain hours, the building has options to store or export to other campus buildings or a power grid.

Fuel energy connections are for district energy systems generating heat or cold, and for buildings for space heating, DHW, and air conditioning. If district energy systems are practicable in a network, individual buildings don't need their own boilers or furnaces, chillers or air conditioners instead they use delivered thermal energy. Thermal energy carriers are energy sources for consumer types of space heating, DHW, and air conditioning in general cases.

4.3.3 NEP Energy Flow Visualization

Once consumer and supplier nodes are added through the NEP input handler module, the types of nodes are determined and nodes are then ready to have directed arcs with a suitable carrier type (See Figure 16) applied to them. The energy flow relationships can be constructed both in the network panel and the dashboard panel. The dashboard panel supports the interface to create a relationship between a supplier and a consumer node (See Figure 17). The details about energy flow direction and the energy carrier used for delivery are reviewed from the network panel, which allows the user to select any of multiple types of carriers from the supplier to the consumer nodes. (See Figure 18). The energy carrier parameters for each node are linked to the EPSCT calculation module after energy flow relations are created or changed. The NEP model updates the calculation output data as well as the graphical view when modifications are made using the network module.

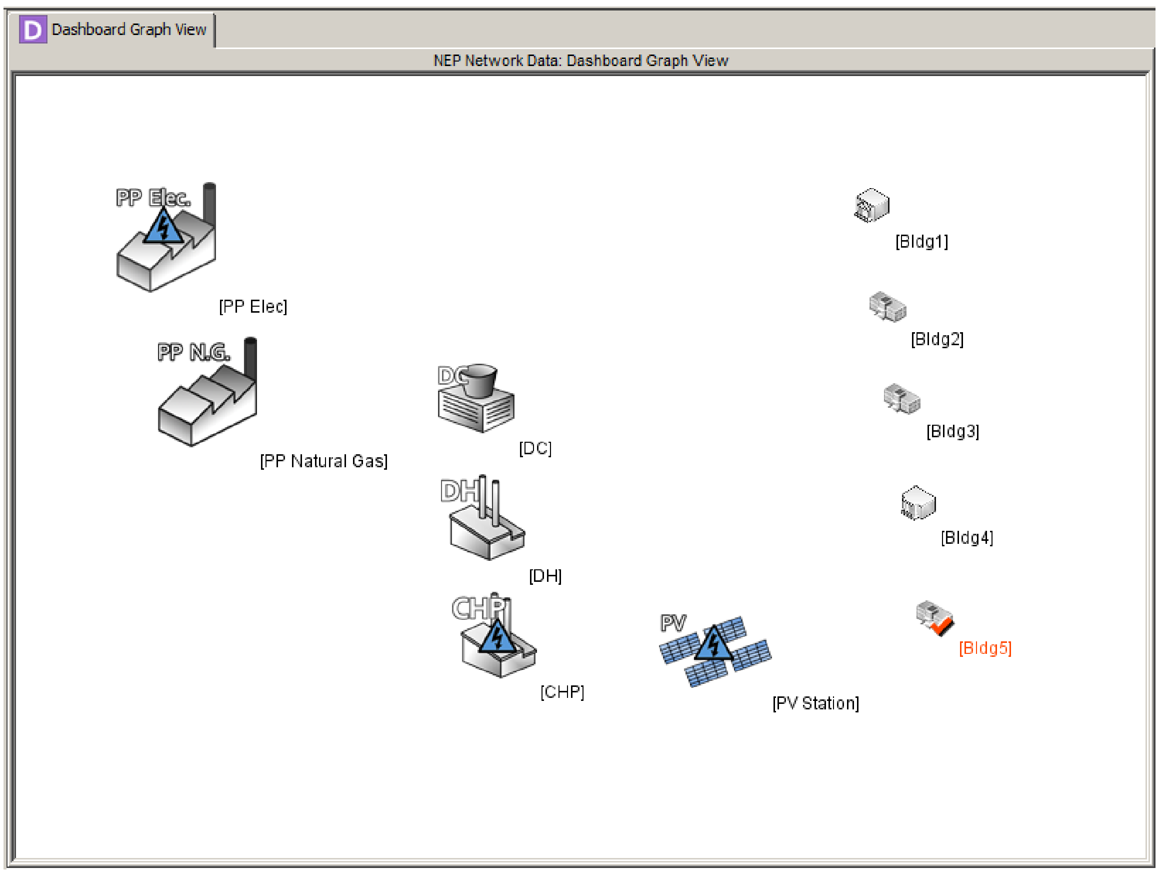


Figure 16 Dashboard Panel Example Prior to Energy Flow Relations

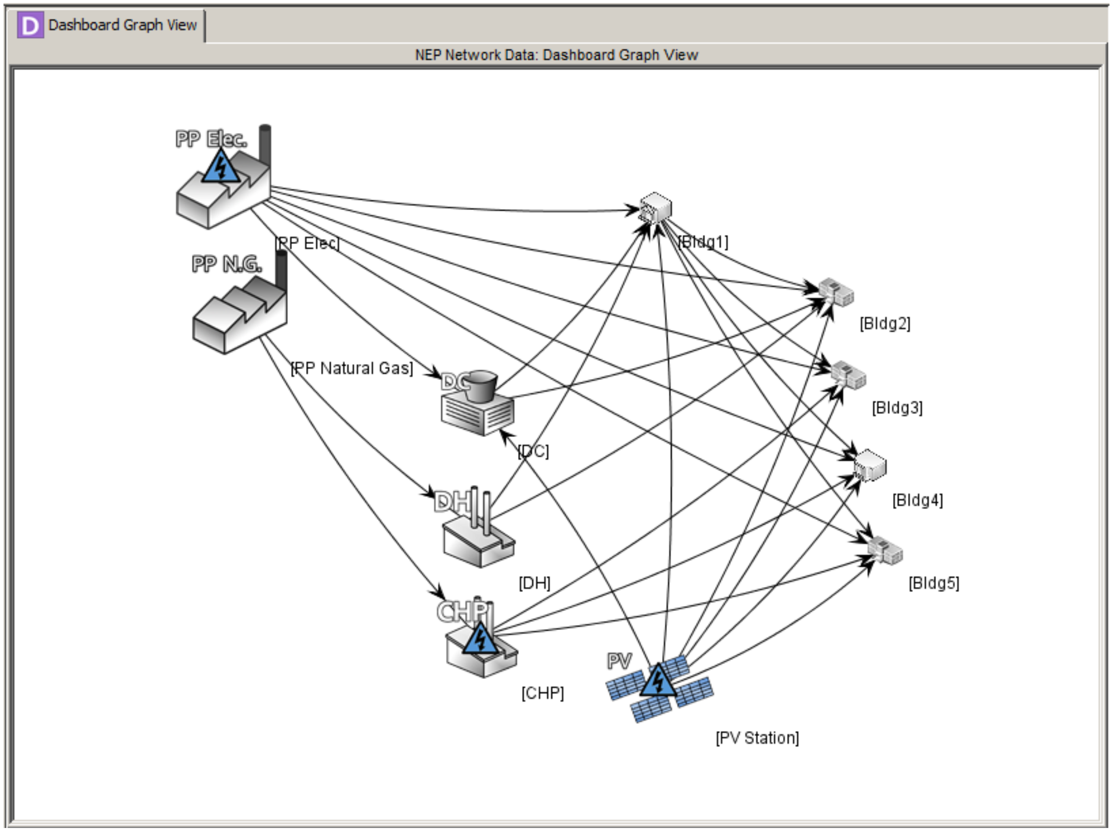


Figure 17 Dashboard Panel Network Energy Flow Visualization Example

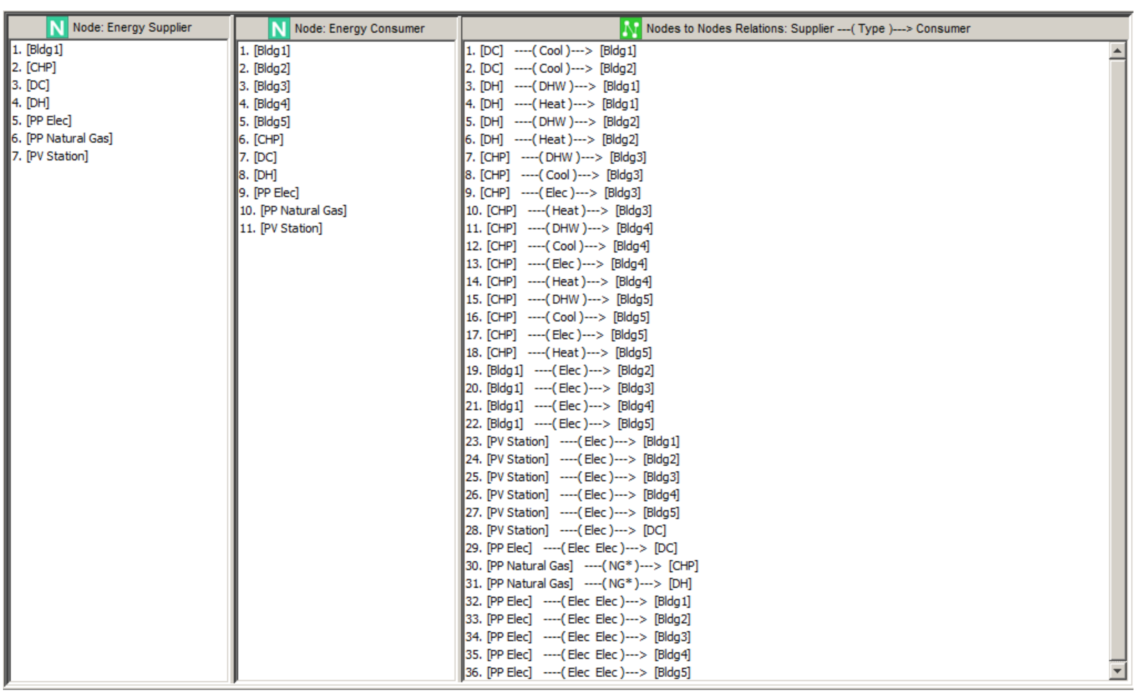


Figure 18 Network Panel Example after Energy Flow Relations

4.4 Reporting Module

The completion of data input in the NEP model enables the estimation of the total expected energy consumption and environmental impacts within the assessment scale. The results of the EPSCT calculation are linked to the NEP model updating the output data for each node and network to provide a total integrated energy performance assessment. As the NEP model adds or removes nodes, or updates the weather data, or inputs data for multiple nodes and the relationships between supplier and consumer nodes, the energy performance data refreshes automatically for a graphical visualization and provides parameters for the delivered energy in multiple nodes at a large scale.

Figure 19 shows available analysis reports that the NEP model can provide at the network assessment scale.

- NEP [Qnd] : Report of hourly data for heating, cooling, DHW, and consumer thermal energy needs for all the consumers in the network
- NEP [Edel] : Report of hourly data of delivered energy for each energy carrier (electricity, fuel for heating, DHW, and cooling consumers) for all the consumers in the network
- NEP [Epri & CO_2] : Report of hourly data of primary energy and CO_2 emissions for each energy carrier (electricity, fuel for heating, DHW, and cooling consumers) for all the consumers in the network
- NEP [Month] : Report of all calculations of thermal energy needs, delivered energy, primary energy, CO_2 emissions, and total gross supported consumers gross floor area in a monthly format (See Figure 20)

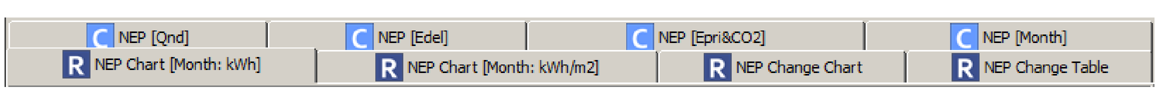


Figure 19 Available NEP Reports for Analysis

DataNum	Field	1	2	3	4	5	6	7	8	9	10	11	12	Year
1	NEP Heating Need [kWh]	86,697.3	51,240.6	6,059.9	1,365.7	11.7	0	0	0	4.4	2,060.8	13,820.7	51,630.7	212,891.7
2	NEP DHW Need [kWh]	8,975.7	7,902	8,710.8	8,352.9	8,975.7	8,352.9	8,710.8	8,975.7	8,088.1	8,975.7	8,617.8	8,446	103,084.2
3	NEP Cooling Need [kWh]	130,115.5	184,893.3	319,515.3	393,800.7	510,942.5	577,612.2	618,686	648,079.8	477,017.4	366,248.3	249,900.6	167,909.6	4,644,721.2
4	NEP Total Thermal Need [kWh] 27044.9 [m2]	225,788.4	244,035.9	334,286	403,519.3	519,929.9	585,965.1	627,396.9	657,055.5	485,109.8	377,284.8	272,339.2	227,986.2	4,960,697
5	NEP Elec Delivered [kWh]	469,874.5	392,265.5	386,725.6	383,093.1	433,920.1	425,184.7	448,189.8	466,940	390,082.6	403,621.3	380,669.3	405,650.8	4,986,217.5
6	NEP Fuel Delivered for Heating [kWh]	0	0	0	0	0	0	0	0	0	0	0	0	0
7	NEP Fuel Delivered for DHW [kWh]	0	0	0	0	0	0	0	0	0	0	0	0	0
8	NEP Fuel Delivered for Cooling in CHP [kWh]	0	0	0	0	0	0	0	0	0	0	0	0	0
9	NEP Total Delivered Energy [kWh] 27044.9 [m2]	469,874.5	392,265.5	386,725.6	383,093.1	433,920.1	425,184.7	448,189.8	466,940	390,082.6	403,621.3	380,669.3	405,650.8	4,986,217.5
10	NEP Elec Primary Energy for Elec[kWh]	1,353,238.5	1,129,724.7	1,113,769.9	1,103,30...	1,249,690	1,224,532	1,290,786.7	1,344,787.3	1,123,437.9	1,162,429.3	1,096,327.5	1,168,274.3	14,360,306.4
11	NEP Fuel Primary Energy for Heating [kWh]	0	0	0	0	0	0	0	0	0	0	0	0	0
12	NEP Fuel Primary Energy for DHW [kWh]	0	0	0	0	0	0	0	0	0	0	0	0	0
13	NEP Fuel Primary Energy for Cooling [kWh]	0	0	0	0	0	0	0	0	0	0	0	0	0
14	NEP Total Primary Energy [kWh] 27044.9 [m2]	1,353,238.5	1,129,724.7	1,113,769.9	1,103,30...	1,249,690	1,224,532	1,290,786.7	1,344,787.3	1,123,437.9	1,162,429.3	1,096,327.5	1,168,274.3	14,360,306.4
15	NEP Elec CO2 Emission [100g]	3,500,564.9	2,922,378.2	2,881,106.1	2,854,044	3,232,705.1	3,167,626.3	3,339,014.1	3,478,703.4	2,906,115.4	3,006,978.6	2,835,986	3,022,098.3	37,147,320.3
16	NEP Fuel CO2 Emission for Heating [100g]	0	0	0	0	0	0	0	0	0	0	0	0	0
17	NEP Fuel CO2 Emission for DHW [100g]	0	0	0	0	0	0	0	0	0	0	0	0	0
18	NEP Fuel CO2 Emission for Cooling [100g]	0	0	0	0	0	0	0	0	0	0	0	0	0
19	NEP Total CO2 Emission [100g] 27044.9 [m2]	3,500,564.9	2,922,378.2	2,881,106.1	2,854,044	3,232,705.1	3,167,626.3	3,339,014.1	3,478,703.4	2,906,115.4	3,006,978.6	2,835,986	3,022,098.3	37,147,320.3

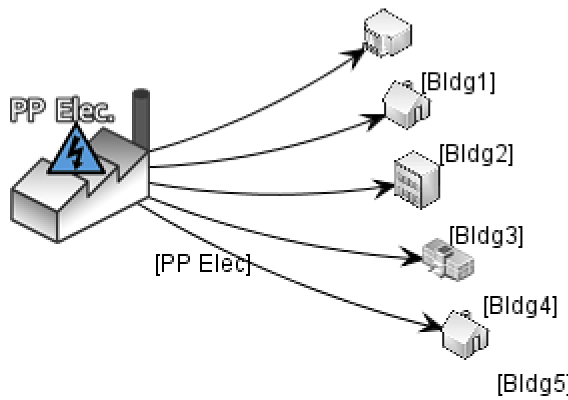
Figure 20 NEP Calculation Results Example in Monthly Format

Five campus buildings and power plants, a district heating and cooling plant, and a PV station are included in the NEP model for the test case. The reporting module generates each report as users update node data or changes the relations for energy efficient design.

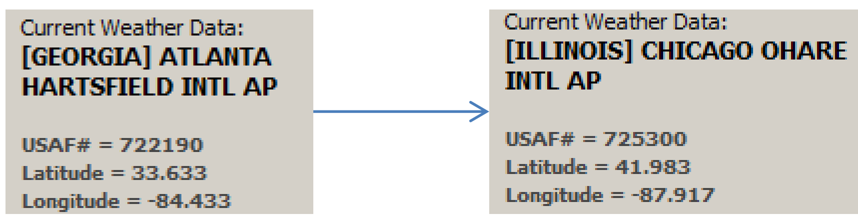
The following sub-sections show how the NEP modules are interrelated, and how they produce the NEP analysis, then present the results in the reporting module using an example case. The network energy design scenarios in the example include:

4.4.1 Assessment Scenarios Impacting the NEP: Example

- 1st NEP Analysis
    - Five campus buildings connected electricity power plant



- 2nd NEP Analysis
    - Change in the weather data

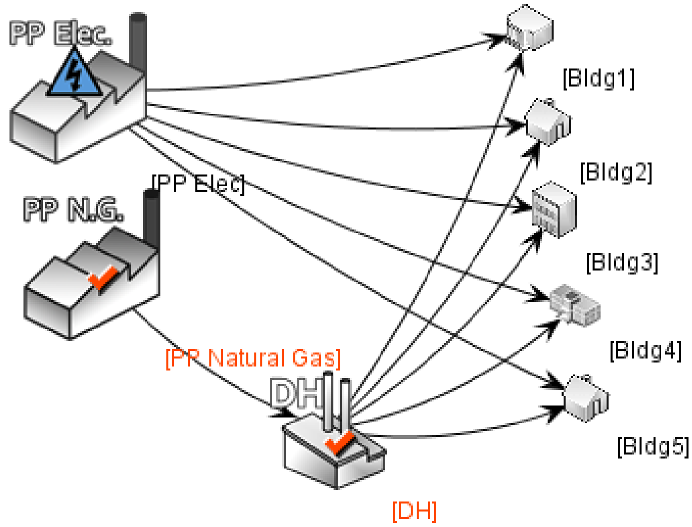


- 3rd NEP Analysis
    - Change in the building data input (20 percent more energy efficient glazing U-value and lighting power intensity all zones)

glazing1	gl_uValue
zone1	zone_light_heat_flow_rate

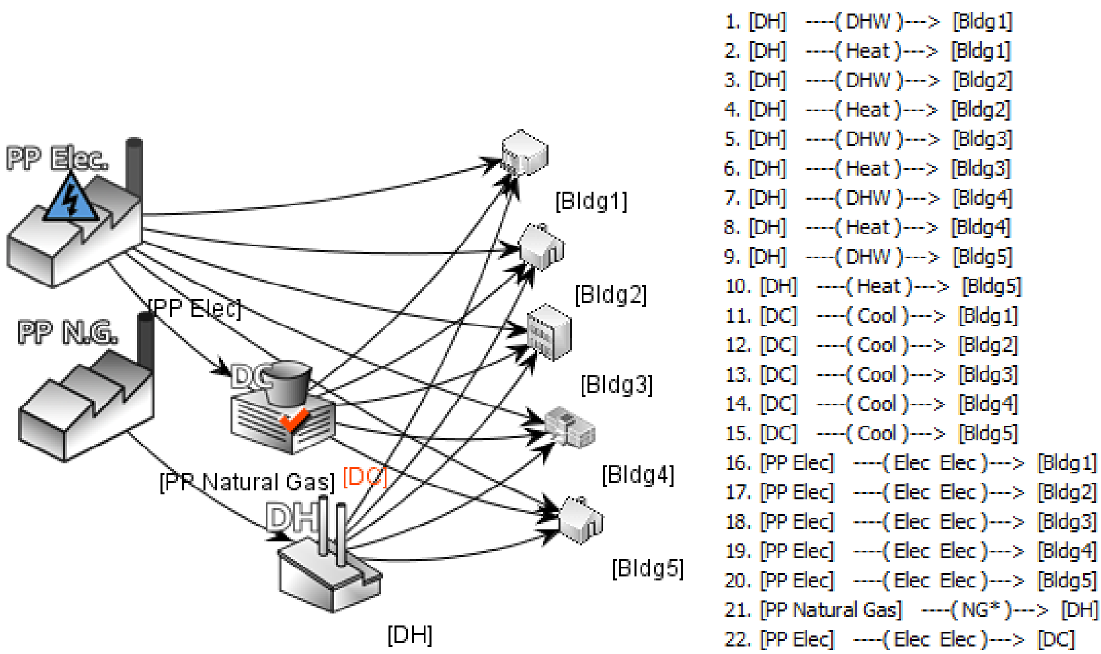
- 4th NEP Analysis
    - Change in the supply system adding a district heating plant for supporting heating and DHW to all buildings

- Change in the supply system adding a natural gas utility

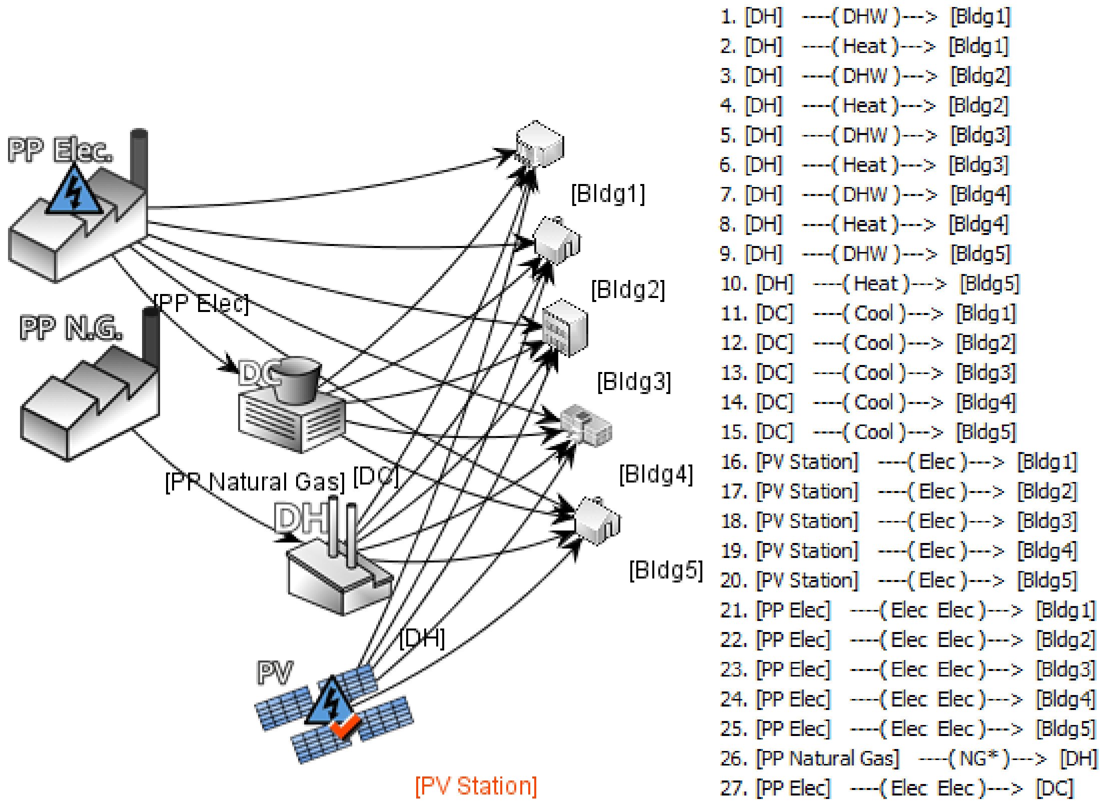


1. [DH] ----(DHW)---> [Bldg1]
2. [DH] ----(Heat)---> [Bldg1]
3. [DH] ----(DHW)---> [Bldg2]
4. [DH] ----(Heat)---> [Bldg2]
5. [DH] ----(DHW)---> [Bldg3]
6. [DH] ----(Heat)---> [Bldg3]
7. [DH] ----(DHW)---> [Bldg4]
8. [DH] ----(Heat)---> [Bldg4]
9. [DH] ----(DHW)---> [Bldg5]
10. [DH] ----(Heat)---> [Bldg5]
11. [PP Elec] ----(Elec Elec)---> [Bldg1]
12. [PP Elec] ----(Elec Elec)---> [Bldg2]
13. [PP Elec] ----(Elec Elec)---> [Bldg3]
14. [PP Elec] ----(Elec Elec)---> [Bldg4]
15. [PP Elec] ----(Elec Elec)---> [Bldg5]
16. [PP Natural Gas] ----(NG*)---> [DH]

- 5th NEP Analysis
  - Change in the supply system adding a district cooling plant for supporting cooling to all connected buildings
  - Change in the supply system adding the electricity flow from electricity power plant to district cooling



- 6th NEP Analysis
  - Change in the supply system adding a PV station for supporting electricity to all connected buildings



4.4.2 NEP Analysis Data Management

In updating the input data or energy supply options, the NEP model provides energy performance changes expressed as percentages compared to the previous scenario. The report keeps the earlier NEP data and shows the performance change log as the network design scenario changes. Figure 21 and Figure 22 show the NEP analysis data log change for the example case as different scenarios are applied to the assessment scale. The NEP change log chart presents the total yearly CO_2 emissions, primary energy consumption, total delivered energy for all carriers, and the heating and cooling needs for all consumers.

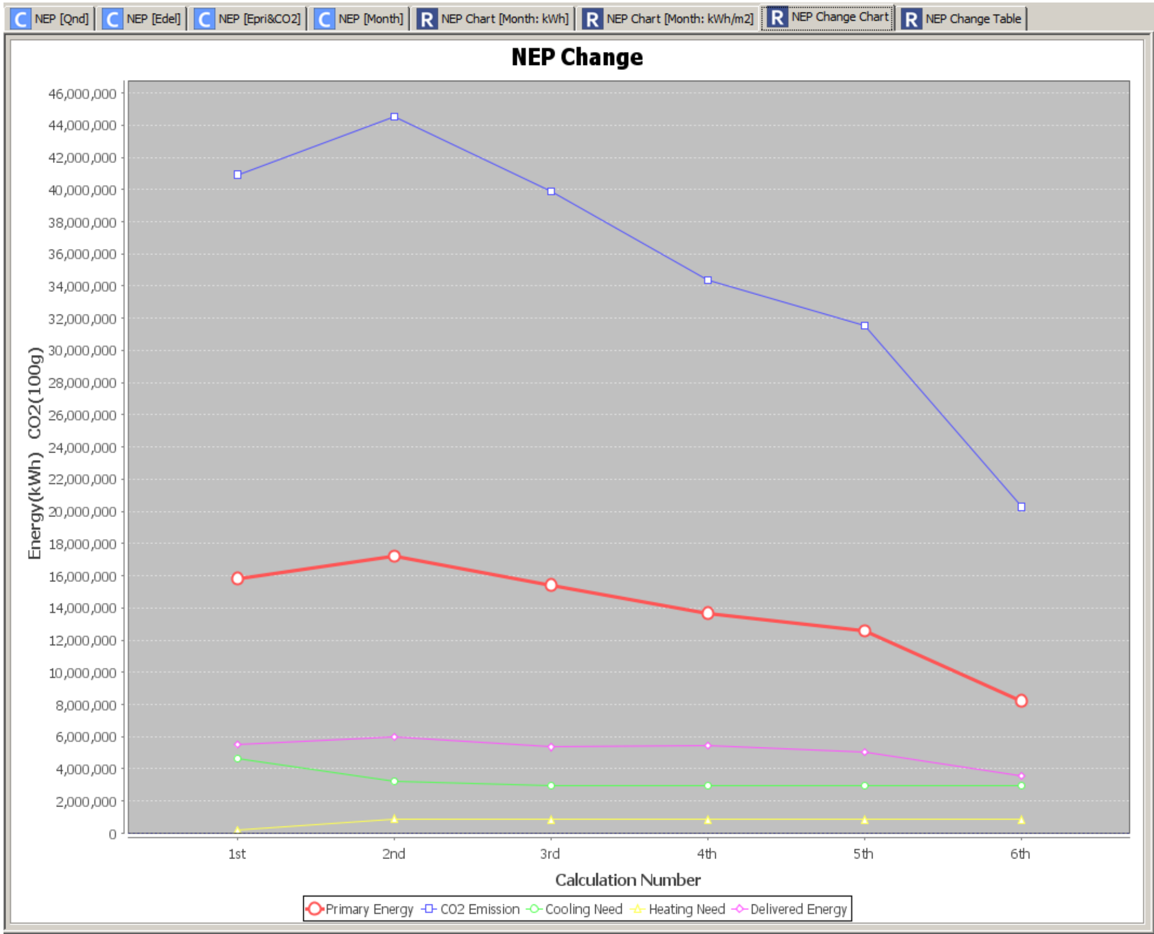


Figure 21 NEP Analysis Data Log Chart Example

Network Calculation Result

DataNum	NEP Heating Need [kWh]	%	NEP Cooling Need [kWh]	%	NEP Delivered Energy [kWh]	%	NEP Primary Energy [kWh]	%	NEP CO2 ...	%
1	212,891.7	0	4,644,721.2	0	5,492,553.1	0	15,818,552.8	0	40,919,52...	0
2	898,114.8	321.9	3,206,437.4	-31	5,978,186.3	8.8	17,217,176.7	8.8	44,537,48...	8.8
3	841,446.9	-6.3	2,953,705	-7.9	5,355,252	-10.4	15,423,125.8	-10.4	39,896,62...	-10.4
4	841,446.9	0	2,953,705	0	5,437,504.6	1.5	13,666,003.1	-11.4	34,369,95...	-13.9
5	841,446.9	0	2,953,705	0	5,060,372.2	-6.9	12,579,861.7	-7.9	31,560,32...	-8.2
6	841,446.9	0	2,953,705	0	3,546,873.6	-29.9	8,220,985.7	-34.6	20,284,75...	-35.7
7	841,446.9	0	2,953,705	0	3,546,873.6	0	8,220,985.7	0	20,284,75...	0

Figure 22 NEP Analysis Data Log Table Example

The model provides various analyses for the quantification of reductions in environmental impact from total primary energy consumption and CO_2 emission reductions from different energy system design options at the building consumer level as well as the energy producing level. The NEP model supports systematic analysis to predict energy consumption and estimate the environmental impacts for a given assessment scale, which helps decision making for the planning of energy supply networks, energy consumption management, retrofit interventions, and more.

4.5 Distinguishing Elements of the NEP model Approach

The NEP approach proposed here is a "lightweight" software tool that supports rapid decision making for energy efficient system design on a portfolio scale in the building sector. There is no deep, dynamic simulation required as the goal is to manage macro design decisions, not micro operational decisions. The hypothesis behind this approach is that an energy performance assessment of each node, based on the normative calculation methods, is accurate enough to support macro, system level decision making. The model is scalable to suit both small and large portfolios and systems and is flexible enough to explore different topologies created by adding or taking away nodes. The main distinguishing feature is the way that nodes and their connections can be managed and manipulated using the graphical interface while the underlying representation retains the capability to reliably calculate (or recalculate) the results at any time. Compared to approaches used in the smart grid or GIS field (mostly based on statistical models with few categorical variables per node), this approach deploys a more accurate and more configurable model. Compared to models for the operation building energy management systems (typically based on real time embedded simulation) the approach uses a lightweight more flexible approach that avoids heavy duty simulation and thus avoids the problems created by intensive modeling efforts such as high cost and ineffective management.

The energy performance assessment of buildings, energy supply and energy generation systems will provide rich information for decision makers, and will help them be strategically positioned when they plan to reduce primary energy consumption and

GHG emissions. The resulting model will help create energy efficient system design based on system wide outcomes, consequently achieving energy savings in the building sector and mitigating environmental impacts.

4.5.1 NEP Software

The NEP model has brought to develop a software to implement the applicability for the thesis. The author also named the software "NEP", retaining the model name. Java was used to program the core calculation and node relation algorithms and the graphical interface. Java was ranked the most popular programming language at 2011 (Tobie, 2012). Thus, the development with Java will be advantageous when the NEP software is integrated with other engineering or design tool. Figure 23 shows the NEP logo. The current version of the NEP software is 1.0.

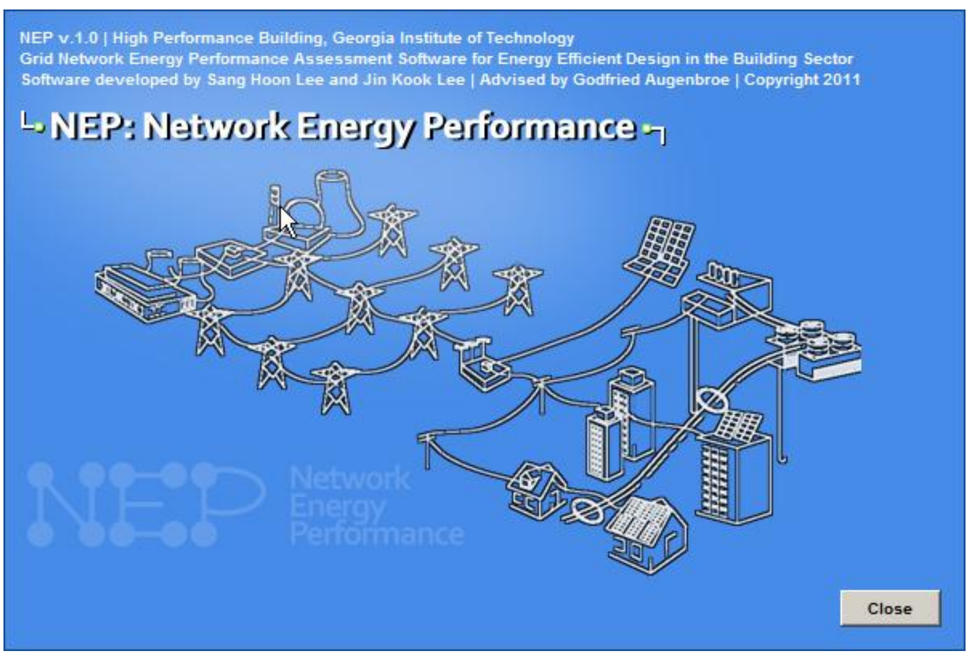


Figure 23 NEP v.1.0 Software Logo

Figure 24 shows the NEP user interface. The main view consists of six panels implementing various functions. The main functions of each panel are as below:

- Weather Data: weather station selection, weather data analysis
- NEP: Node: node input data management, node energy performance analysis
- NEP: Network: energy flow (carrier and consumer type) relation management
- NEP: Dashboard: graphical view of network nodes and directed graph connecting between nodes
- NEP: Report: NEP analysis view
- Console Panel: system configured message view

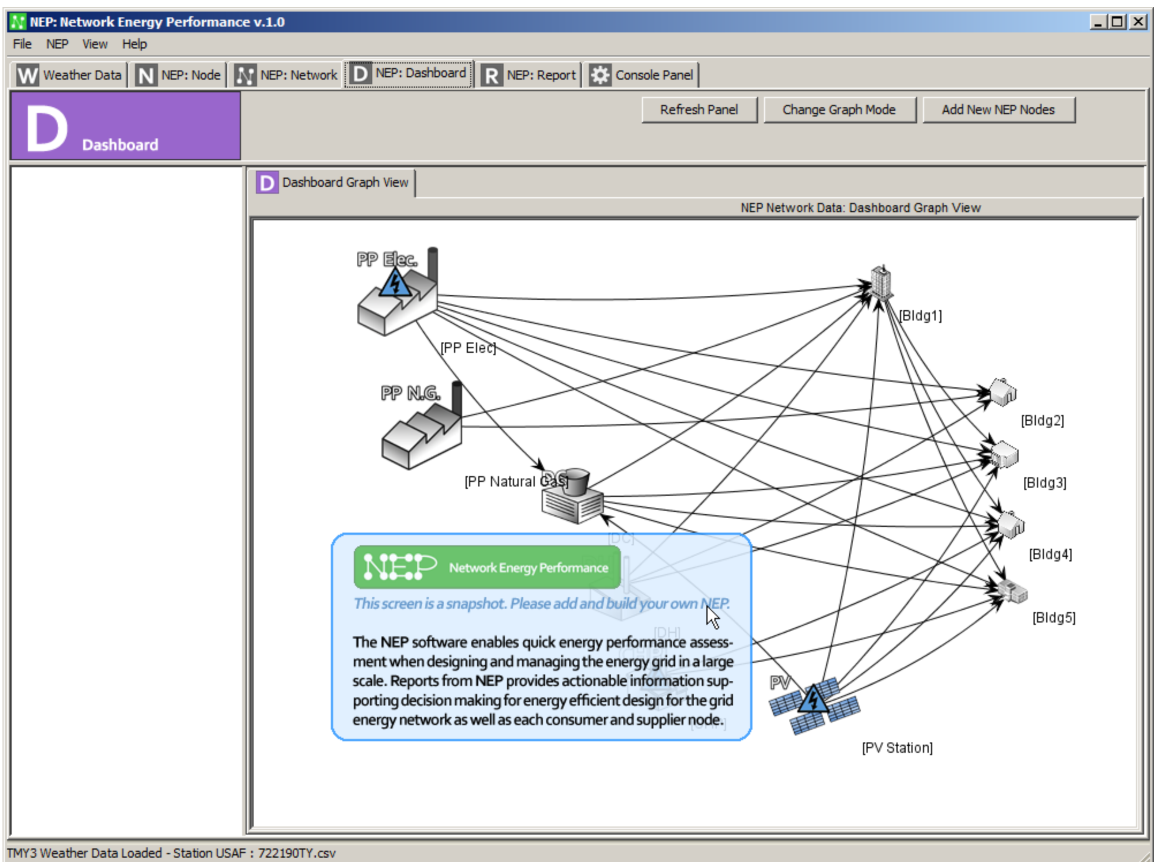


Figure 24 NEP v.1.0 User Interface

4.5.2 Modeling and Calculation Time Statistics

The time required for modeling and calculation is crucial when with the software user is working with multiple design scenarios. This becomes even more important in the energy performance assessment for a large scale system such as a campus or a portfolio of many buildings (for example, about 100 buildings) and energy producers. Users may have encountered difficulty with the slow modeling and calculation speeds of existing energy simulation applications. They do not even try using energy simulation applications for a large-scale energy performance assessment because of all the modeling, updating design options, and integrating total outcomes in the assessment scale. Before the NEP software was available, the author developed the EPSCT calculator using Microsoft Excel to implement the NEP model as a core engine. The Excel version calculator became overburdened taking care of the calculation process as modules were added, and the data set eventually represented 8,760 hours. It turned to be ineffective in dealing with multiple nodes and relations between multiple building and supplier nodes. It took approximately one minute per building node on average to calculate the primary energy CO_2 emissions in the assessment scale. To resolve these intractable issues for a large-scale energy performance assessment, the NEP software was developed.

The Console Panel was added in the software to measure the time elapsed for each assessment for a single building node as well as total network calculation. Below shows the statistics from the Georgia Institute of Technology (Georgia Tech) campus case study which will be introduced in the next chapter.

Calculation Time Fact using NEP v.1.0:

- When loading and calculation a single building to NEP: 0.3 seconds on average
- When recalculating a single building in NEP: less than 0.3 seconds

- When calculation total NEP with relationships: 0.2 seconds per building in average

CHAPTER 5

CASE STUDY

A case study using the NEP software was conducted to analyze campus energy performance assessment with various options of the building level and supply level energy reduction. The case study collected campus-scale data for 30 buildings and energy supply system data from the Georgia Tech. Campus energy performance with the assessment scale was analyzed with different scenarios for energy supply options and building level retrofit interventions.

5.1 The Georgia Tech Campus

5.1.1 Energy Distribution Statistics

Georgia Tech is located in midtown Atlanta, Georgia. The Total number of institute buildings is 238, and the total building gross area is 1,339,164 m2. The major energy carriers are electricity, chilled water, steam, and natural gas to meet buildings' energy requirements. Georgia Tech is one of the largest consumers of electricity in the Atlanta area. The campus owns and manages an electrical substation, which has 80 megawatts of instantaneous capacity. The campus master electricity substation supports 80 % of the electrical power demand for the campus. Three chiller plants generate and supply chilled water for air conditioning and other needs. The Holland Power Plant has six chillers with capacity of 8,000 tons of cooling, while the 10th Street Plant has five chillers capable of producing 9,250 tons, and the Tech Square Plant has 2 Chillers with 1,700 tons of cooling capacity supporting the Tech Square area at the edge of campus. Other buildings which are not served by chiller plants have their own smaller stand-alone chillers or chiller-like units to meet the cooling demand. The major energy source for heating is steam from central steam boilers, with a supply of propane available as a backup fuel source for some sites. The steam plant is capable of producing 200,000 pounds of 150 psi steam every hour. In addition, there are 30 smaller boilers used for buildings that are not served by central steam. Georgia Tech campus boilers use natural gas as fuel. The largest natural gas user is the central steam district heating plant.

5.1.2 Georgia Tech Modeling Data

30 campus buildings and the associated local energy producing systems were modeled. Building data and campus-wide electric and thermal energy supply system data were obtained from the Georgia Tech Facilities department.

Figure 25 shows the selected buildings on the Georgia Tech utility map, including energy consumers and suppliers with the type of connected energy supply for those buildings color coded. The full list of the selected 30 Georgia Tech buildings is in Appendix B. Building operation and internal activities data was based on standardized data from various European standards and reports. The operation data used for the modeling works are provided in Appendix C: Standardized space activity and operation schedule. For the environmental impact quantification from electricity delivered from the power plant, a source energy factor of 3.364 (Deru & Torcellini, 2007) and CO_2 equivalent emission rate 640g/kWh (EPA, 2011) was used based on data for the state of Georgia. For the fossil fuel environmental impact factor for natural gas used, the data of source energy factor was 1.0 and CO_2 emission factor data was 180 g/kWh (EPA, 1998).

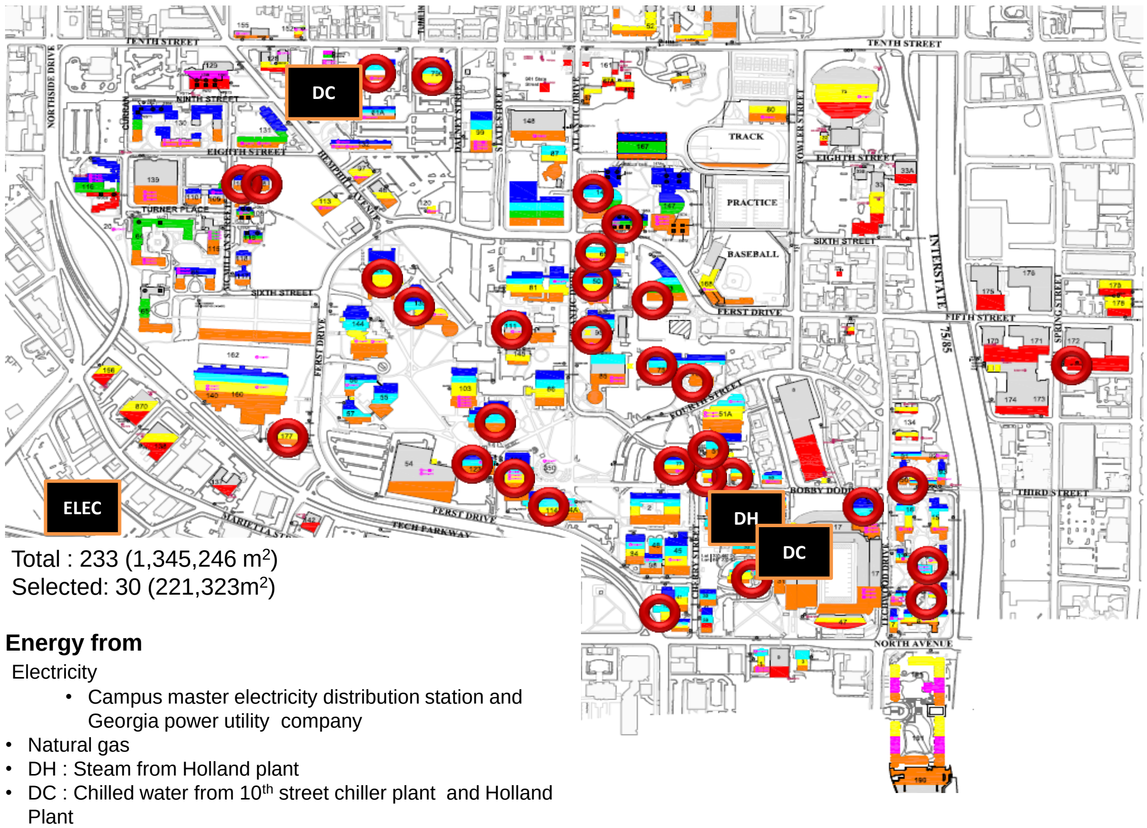


Figure 25 Georgia Tech Campus Utility Map

5.2 NEP Calculation Validation

All selected buildings were first evaluated using EPSCT, which is embedded in the NEP tool. At the same time, all buildings were modeled in a simulation application, DesignBuilder. DesignBuilder uses EnergyPlus as a core engine providing a user friendly interface to carry out simulations that relay on the EnergyPlus simulation program. EnergyPlus is one of the most widely used building energy simulation applications in the energy modeling industry. Inputs in NEP and DesignBuilder were kept consistent for the purpose of validating the NEP calculation results.

shows the NEP calculation and DesignBuilder simulation results for the Georgia Tech campus baseline case. The results include the thermal energy demand, which is the sum of the heating and cooling demand and the delivered energy including electricity and natural gas. All values are normalized by the campus gross building floor area. It shows that the thermal energy demand determined by the NEP tool is 4.9% greater than, and the delivered energy is 19.6% less than the simulation result.

Table 7 NEP Calculation Validation Comparing with Simulation

	NEP / EPSCT	DesignBuilder / EnergyPlus	Difference
Thermal Energy Demand (kWh/m^2/year)	150.1	143.1	4.9%
Delivered Energy (kWh/m^2/year)	180.2	224.0	-19.6%

This explains that the normative calculation method using the NEP tool to assess the thermal energy demand by the dynamic interactions between the envelope, environment, and internal activities is accurate enough. The interval of confidence is only 4.9%, which is smaller than an acceptable interval of confidence of 10% (Tronchin & Fabbri, 2008). The difference in the delivered energy between the NEP tool and DesignBuilder is not related with the input data, but rather it is caused by the calculation model. Although the thermal energy demand is close enough, the calculation algorithm of the NEP tool does not reflect dynamics of the partial load efficiency especially in the cooling and heating system. The chiller and boiler rarely be operating at full load, and partial load efficiency is generally lower than the nominal full load efficiency. Also, HVAC system provides simultaneous heating and cooling in multi-zone simulation models. This often occurs during the intermediate season under different internal heat gain conditions. The unintentional heating and cooling overlap causes the energy waste because heating and cooling systems operate to negate each other. These are some reasons that the delivered energy from the NEP tool is than the simulation results. Further research may be needed to calibrate the normative model in delivered energy system level, which contributes CEN / ISO calculation standards updates.

5.3 Georgia Tech Campus NEP Model

At the initial setup for the Georgia Tech case in the NEP model, supplier nodes are set up according to the current practice to include an electrical power plant and delivered natural gas as a global supply node and a district heating and district cooling system as a local energy supply network node. Figure 26 shows all nodes added in the NEP application from the dashboard panel view.

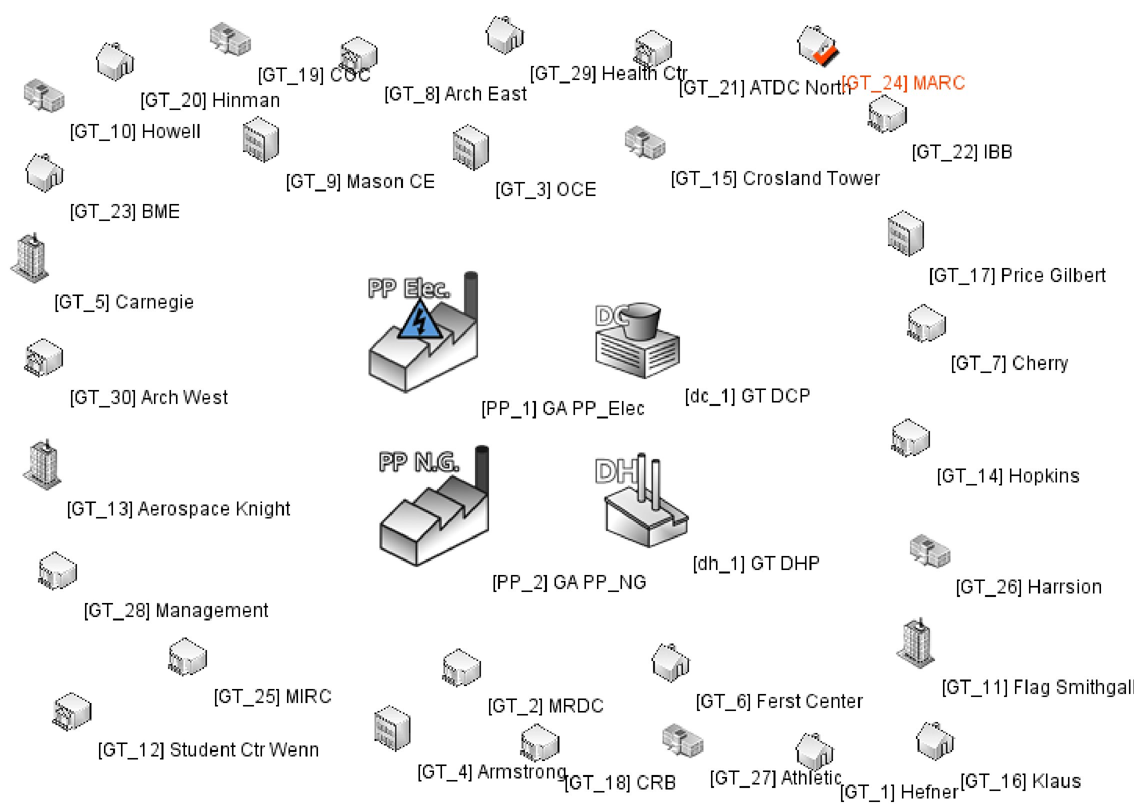


Figure 26 Nodes Added in NEP: Georgia Tech Campus Case

5.3.1 Campus Scale Energy Performance Assessment

This subsection demonstrates campus level energy performance assessment with the NEP application constructing energy consumers and suppliers. Then, the case study further analyzes the energy performance with energy reduction scenarios in both energy consumption and supply nodes. The outcomes from the case study enables estimation of the total environmental impacts of primary resources and CO_2 emissions with different scenarios for energy supply topologies and energy system design at a campus scale.

5.3.1.1 Energy Performance Base (As Is)

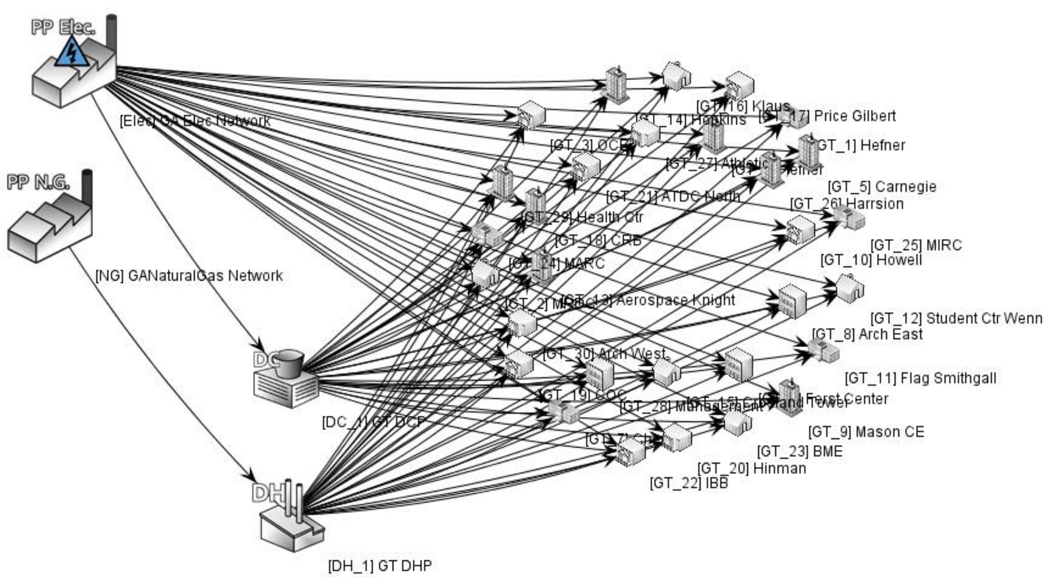


Figure 27 NEP Dashboard View of Georgia Tech Campus Energy Flow Constructing Suppliers and Consumers “As-Is”

Figure 27 visualizes the energy flow network of the Georgia Tech campus "as-is"; the baseline case constructs energy directed arcs from suppliers to consumers. The baseline case consists of the district heating plant burning natural gas and generating steam, a district cooling plant equipped with electrical chillers, and 30 diverse functional types of buildings as energy consumers. The total gross floor area of the selected buildings is 219,501m^2 with 23 different functional zones, as described in Appendix C. No buildings in the base case have a heating or cooling system on-site, but the central plants distribute thermal energy via a network of insulated pipes. A distribution loss of 10% was used for the Georgia Tech case, which is a typical annual thermal energy loss efficiency in district networks (CEN, 2007b). The maximum cooling loads for buildings are 17,651 kW on August 1st at 5:00 p.m. The multiple chillers with a COP of 4.45 from the Georgia Tech district cooling plants generate chilled water to meet the cooling requirements for the 30 buildings. The district heating plant requires 8,015 kW at the peak heating load, which occurs on February 12th at 7:00 a.m.. Boilers with a COP of 0.75 at the district heating plant generate steam and distribute it throughout the campus. Charts in Figure 28 show the NEP calculation results normalized by the gross building area at the network scale in a monthly format. The resolution of the analysis deals with; the hourly energy performance of thermal energy needs for heating and cooling for each consumer and/or the aggregate total network, the delivered energy for each energy carrier for electrical power from the Georgia energy grid or natural gas for the energy systems in the campus district plants as well as building energy consumers, and consequential impacts in primary energy and CO_2 emissions.

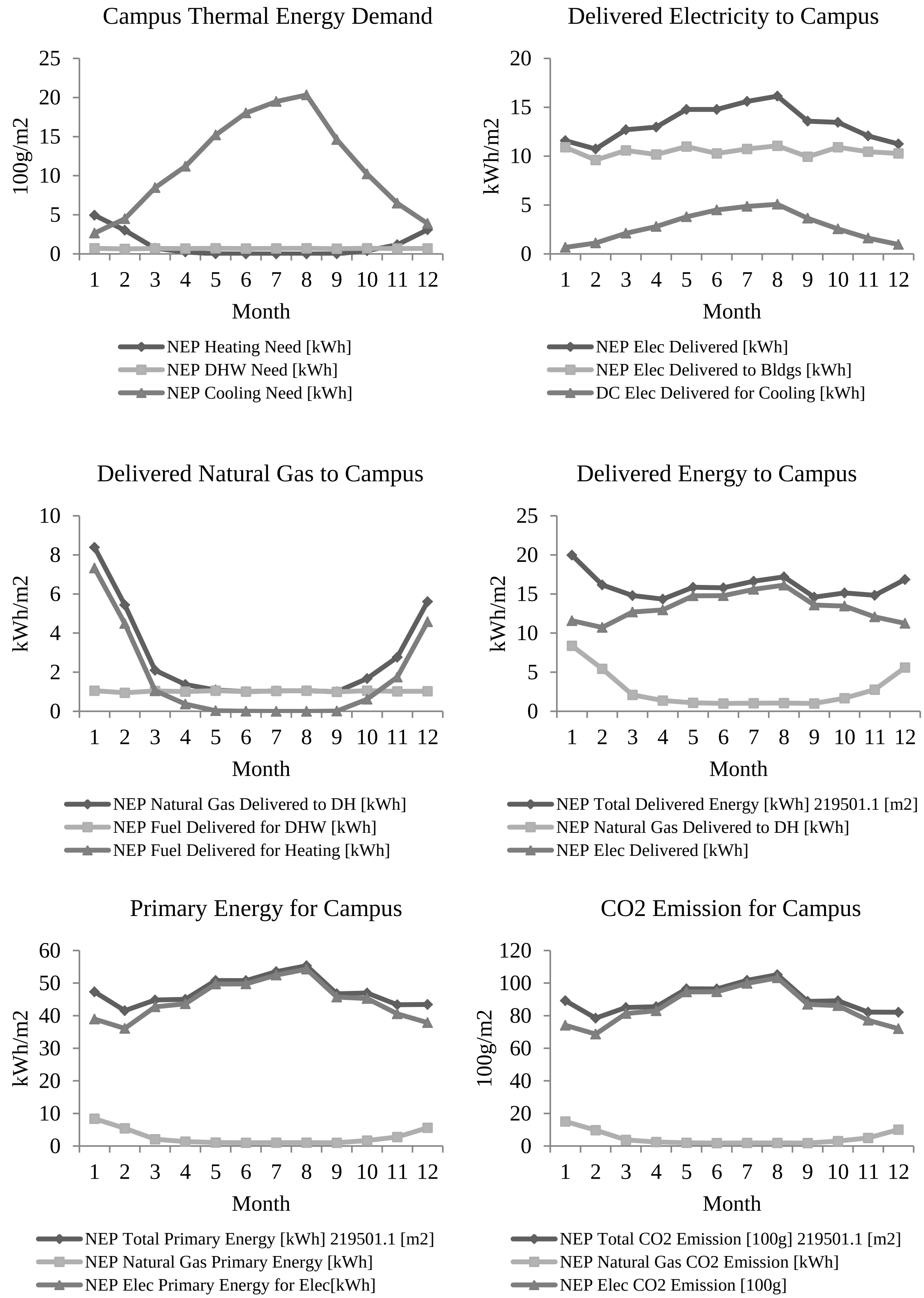


Figure 28 Georgia Tech Base Case Network Energy Performance Calculation Results

The energy performance of the base case was established as the basis to study energy efficiency retrofits with different options in the energy supply typologies and for incorporating systems on a large scale.

5.3.1.2 Energy Performance with Retrofit Scenarios

Analyses were conducted as part of the case study to improve energy performance on a campus scale. The campus energy performance improvements were from retrofits in energy supply systems, as well as additional energy efficiency resulting from retrofits to the buildings. Six scenarios were tested after discussions with Georgia Tech Facilities. The scenarios were not for making optimal decision making to reduce campus-wide CO_2, but for providing information to Georgia Tech Facilities where they were interested in for campus-wide energy supply system retrofits. This may lead to a limitation of the scenario study causing the comparison is not meaningful.

Selected scenarios are as below:

1. Existing District cooling plant cold generation efficiency retrofit
2. Existing District heating plant boiler heat generation efficiency retrofit
3. Adding cogeneration (heat and electricity) to the existing district heating plant
4. Adding trigeneration (heat, cold, and electricity) to the existing district heating plant
5. Adding a district level PV station
6. Adding BIPV panels on dormitory buildings exporting surplus electricity to other buildings

The following sections describes each scenario with applied retrofit technologies, and reports how much CO_2 emissions can be reduced from the selected scenario.

1. Efficiency Improvement in District Cooling Plant Chiller Compressor Retrofit with Turbo Compression Chiller

The first analysis in the case study applied retrofits in chillers for improving the thermal generation efficiency of the cooling plant. Turbo compressor chillers can reach a COP of 5.9 when the system serves multiple buildings with a capacity greater than 800 kW (CEN, 2007a). The retrofit scenario substituted a COP 5.9 instead of the COP 4.45 of the district cooling chillers. Figure 29 and Figure 30 visualize a campus wide utility map showing buildings that impact the performance in chillers. The retrofit scenario does not require changes in energy flow arcs in the NEP modeling. Figure 31 shows annual energy savings and monthly breakouts at a campus scale from the district cooling system retrofit. Figure 32 shows the electricity demand reduction from the power grid at the peak cooling load hour on August 1st at 5:00 p.m. The chiller retrofit in district cooling plants can reduce electricity peak consumption by 8.6 %.

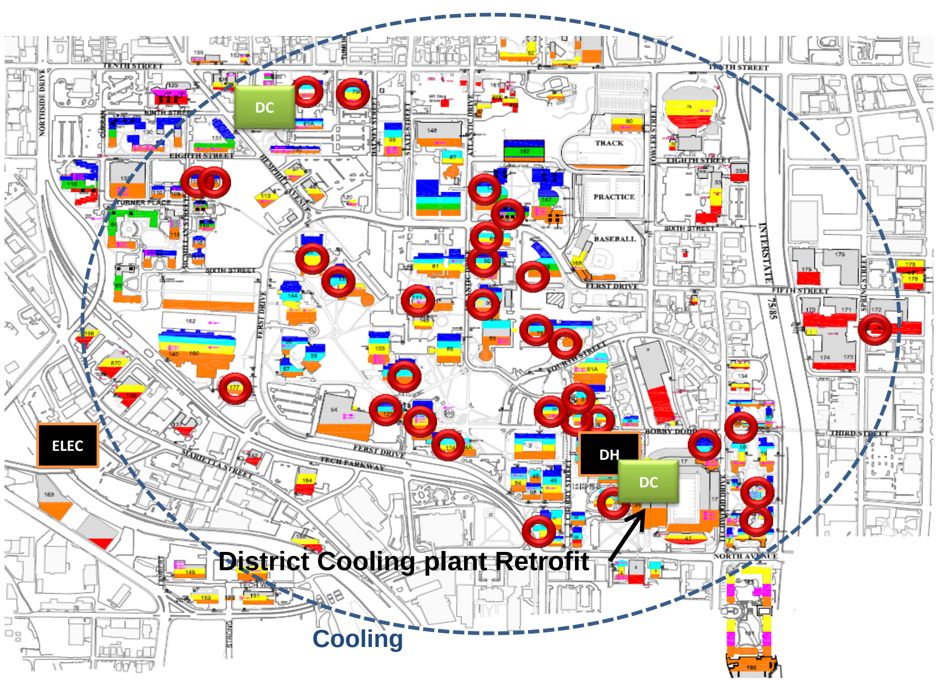


Figure 29 District Cooling Plant Retrofit Impact to the Campus

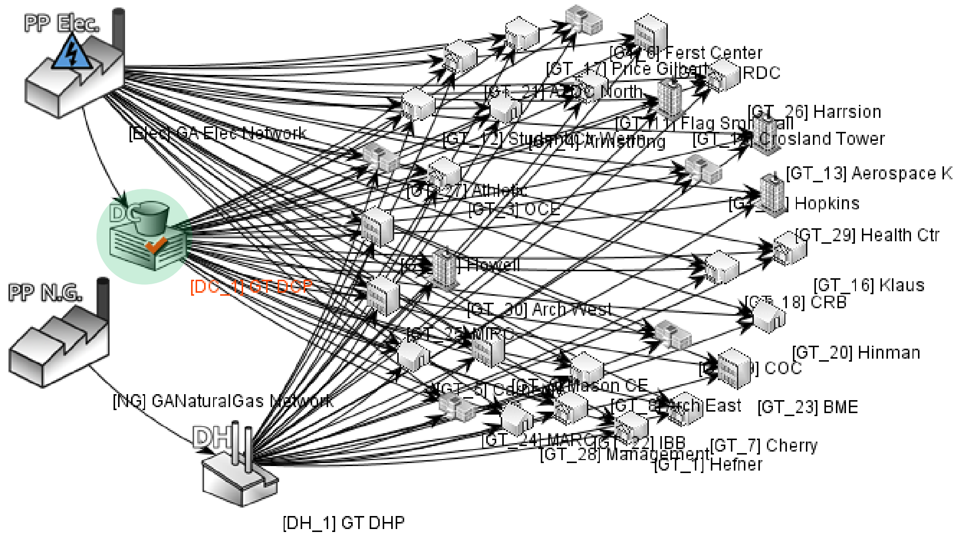


Figure 30 District Cooling Plant Retrofit Scenario Modeling in NEP Dashboard

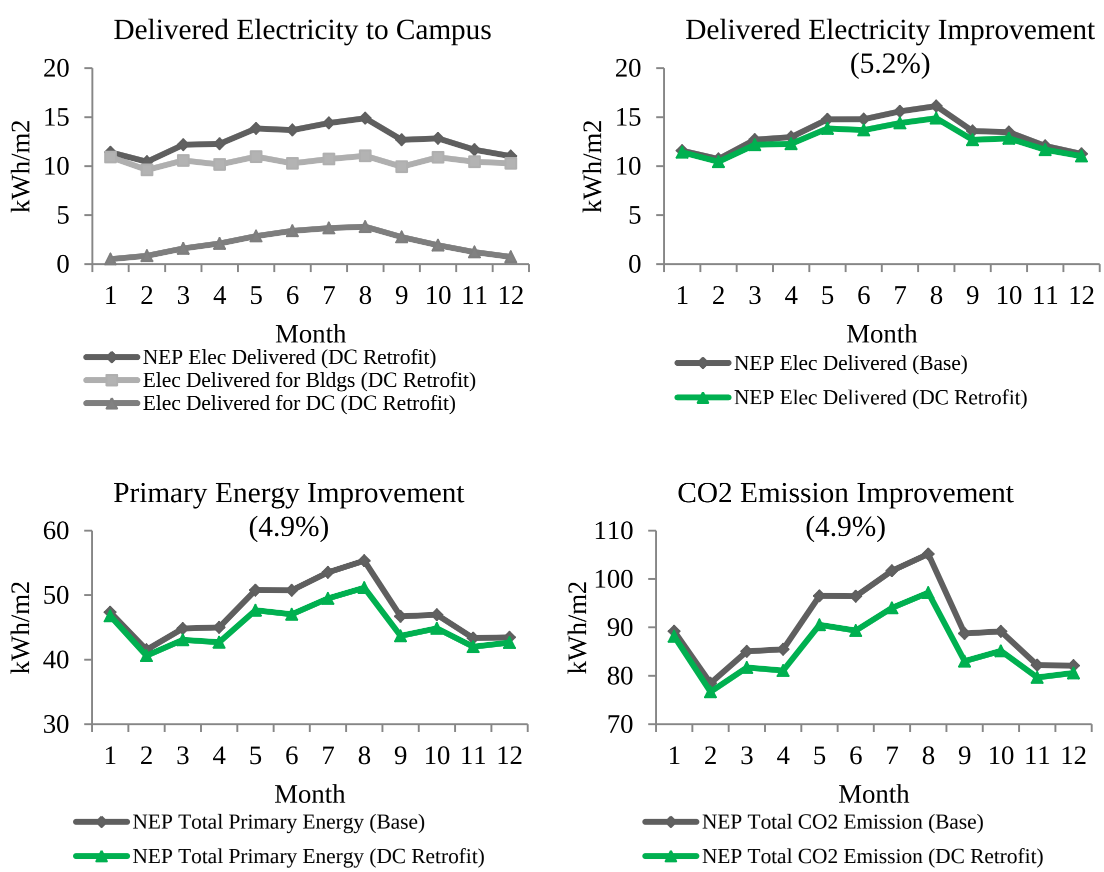


Figure 31 Campus Energy Savings from District Cooling Plant Retrofit

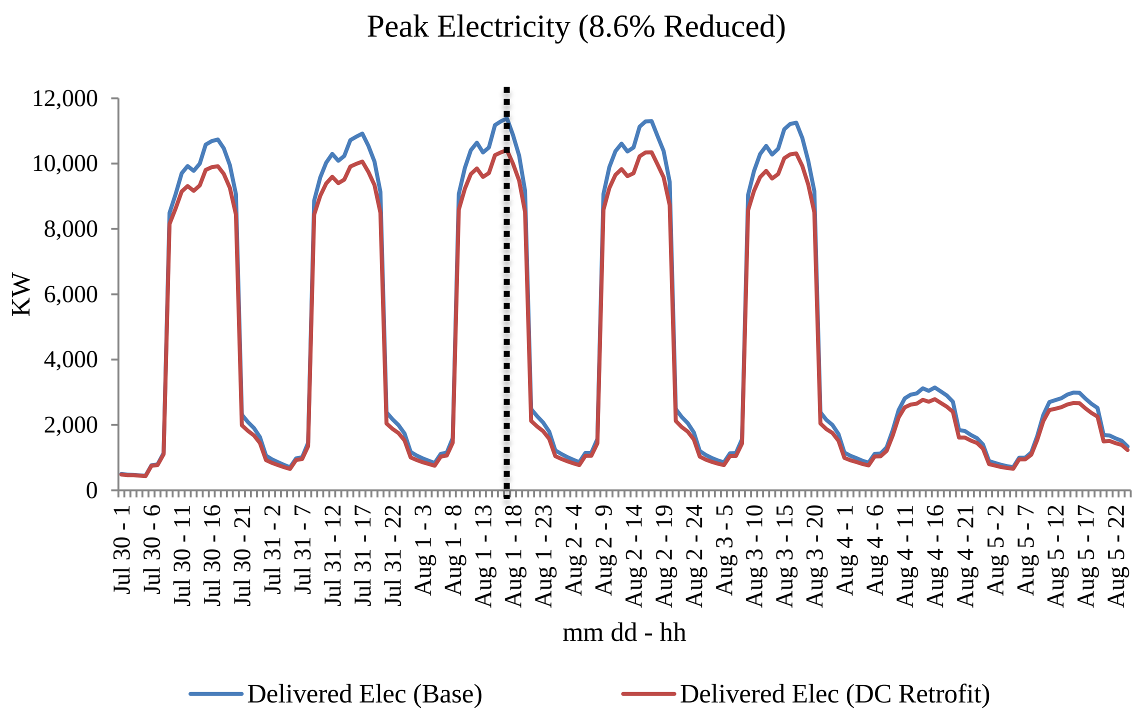


Figure 32 Peak Electricity Demand Reduction from District Cooling Plant Retrofit

2. Efficiency Improvement in District Heating Plant Boiler with Exhaust Gas Condenser

The second analysis was a retrofit in the heat generating boilers in the district heating plant. Boilers with a COP of 0.95 which have exhaust gas condensers were added to the retrofit scenario, replacing conventional gas boilers with a COP of 0.75. The COP values for district heating plants were referenced from an EPA publication (EPA-NR, 2007), the values from which were derived for heating energy consumption calculation with the normative calculation method. Figure 33 shows the buildings that create the heating demand for the district heating plant. The retrofit scenario modeling in Figure 34 does not require changes in the relationships between suppliers and buildings. Figure 35 shows the reduced natural gas consumption and CO_2 emissions at a campus scale from the district heating system retrofit. Although natural gas reductions are expected to be 21.1%, primary energy (1.2%) and CO_2 emission (1.1%) reductions are less significant. Because the retrofit is only for the boiler system using natural gas, electricity consumption does not have any impact from such a retrofit when considered at the campus-wide scale. The delivered electricity will be more significant when impacts of primary energy and CO_2 emissions are evaluated (See 5.1.2 for primary energy factors and CO_2 emission coefficients for the energy grid for Georgia).

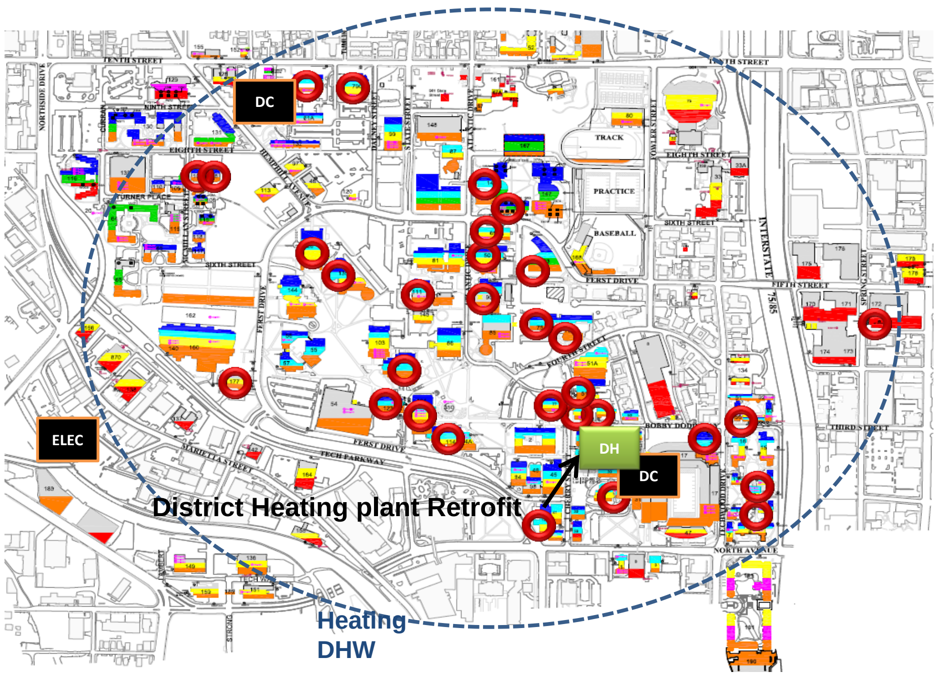


Figure 33 District Heating Plant Retrofit Impact to the Campus

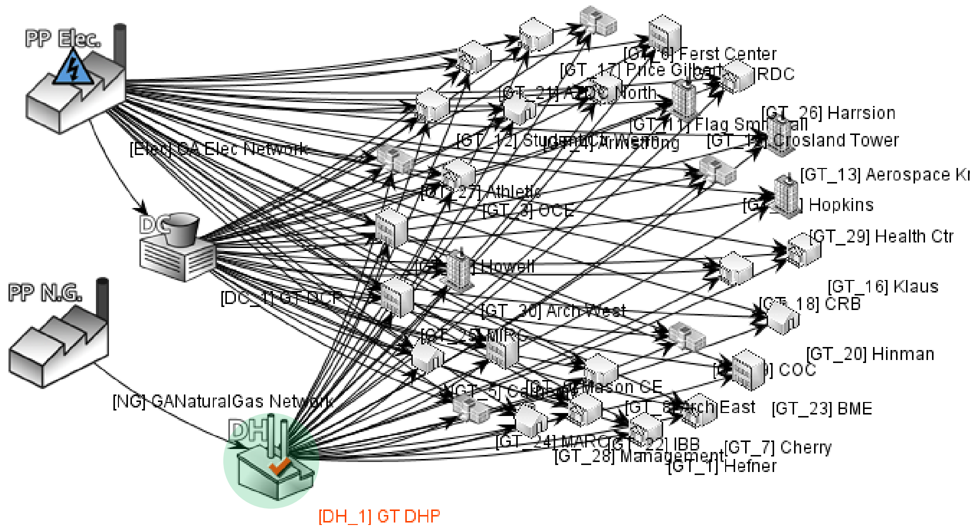
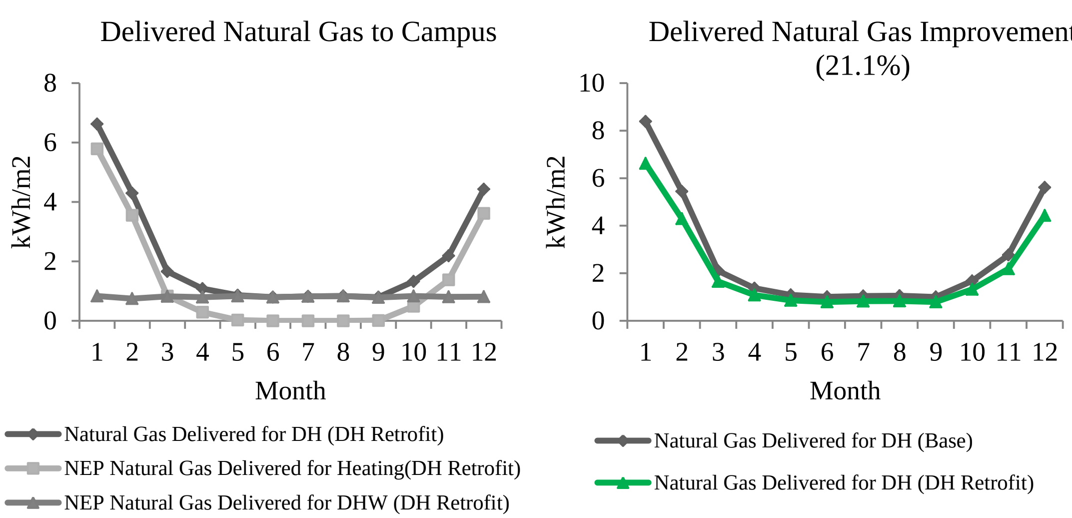


Figure 34 District Heating Plant Retrofit Scenario Modeling in NEP Dashboard



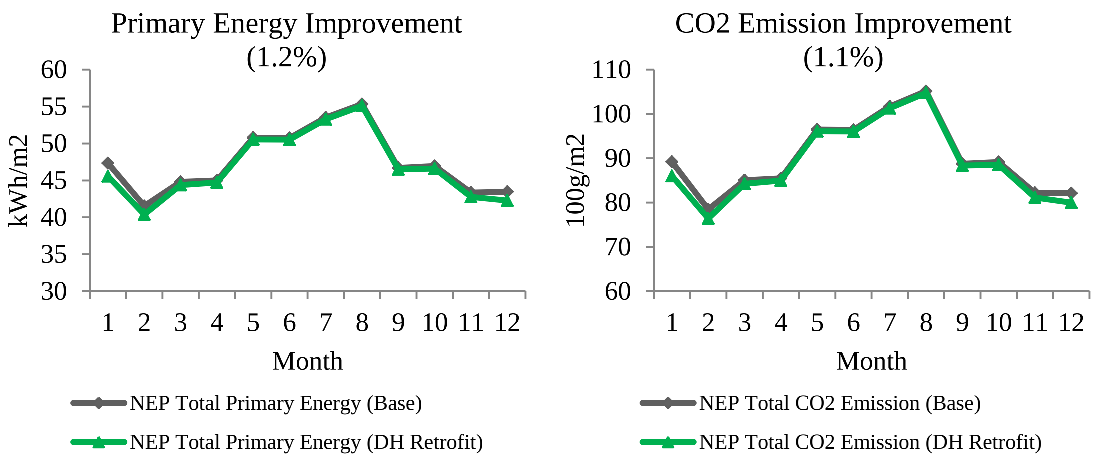


Figure 35 Campus Energy Savings from District Heating Plant Retrofit

3. CHP Cogeneration: CHP replacing DH natural gas combined cycle supporting heating and DHW
    - Ratio of natural gas cogeneration fuel input to electricity or useful heat output: 0.8
    - Heat production efficiency of 0.44, electricity generation efficiency of 0.36
    - Ratio of Electricity to Useful Heat in Cogeneration of 0.8 : 1

The case study also evaluated a cogeneration from the CHP plant. The retrofit for the CHP plant would replace the district heating plant used in the baseline case study in meeting the heating and DHW demands from campus buildings. The CHP plant uses natural gas as a fuel input source to generate steam and electricity from internal combustion engines with a combined cycle. The representative heat production efficiency is 0.44 and the electrical power generation efficiency is 0.36, based on a nominal load (Harvey, 2006). Figure 36 shows buildings in the utility map of which steam and electrical power are served by the newly installed CHP plant. Figure 37 visualizes the retrofit scenario modeling in the NEP dashboard where the district heating plant has been replaced with the CHP.

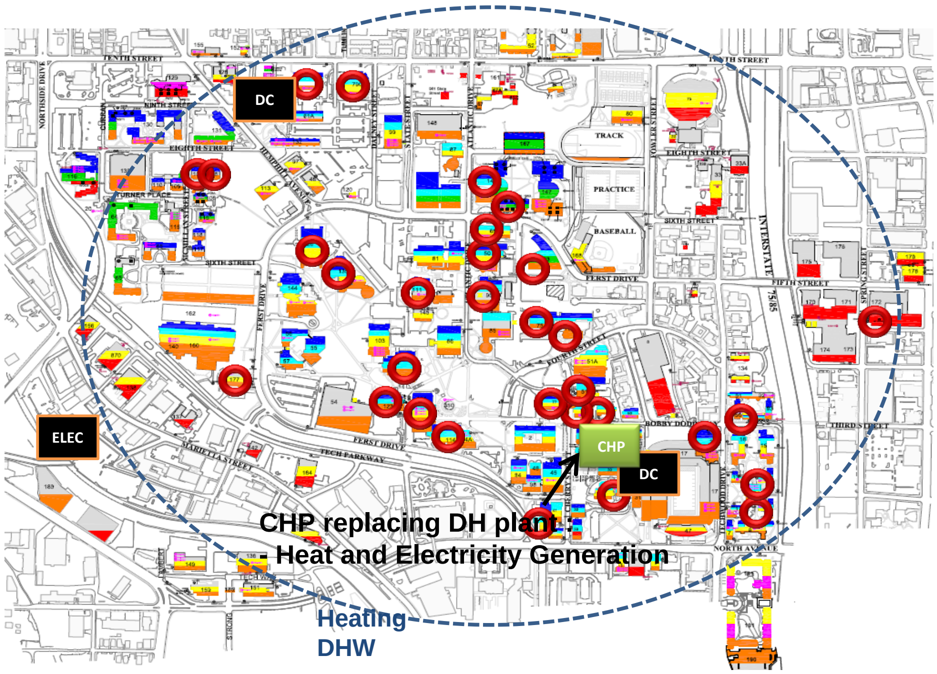


Figure 36 CHP Cogeneration Retrofit Impact to the Campus

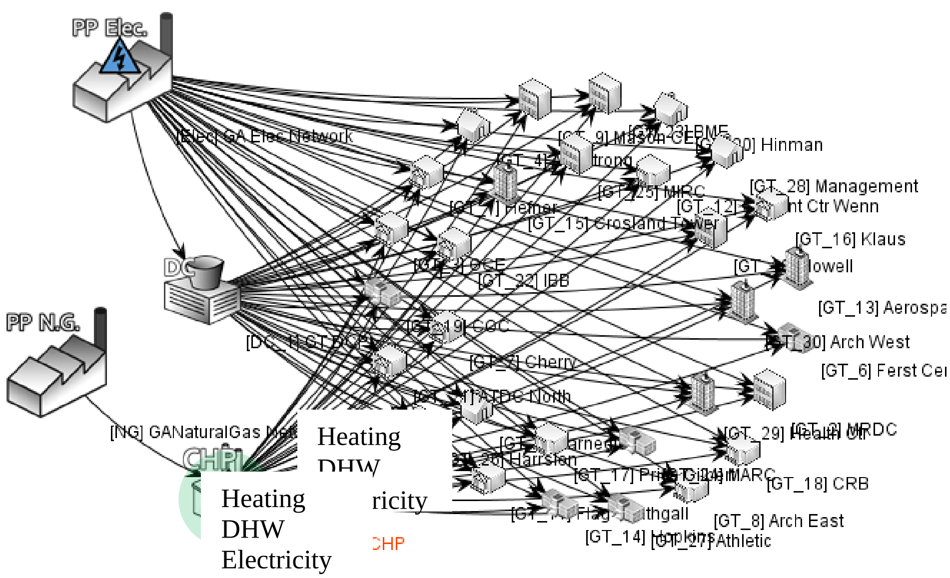
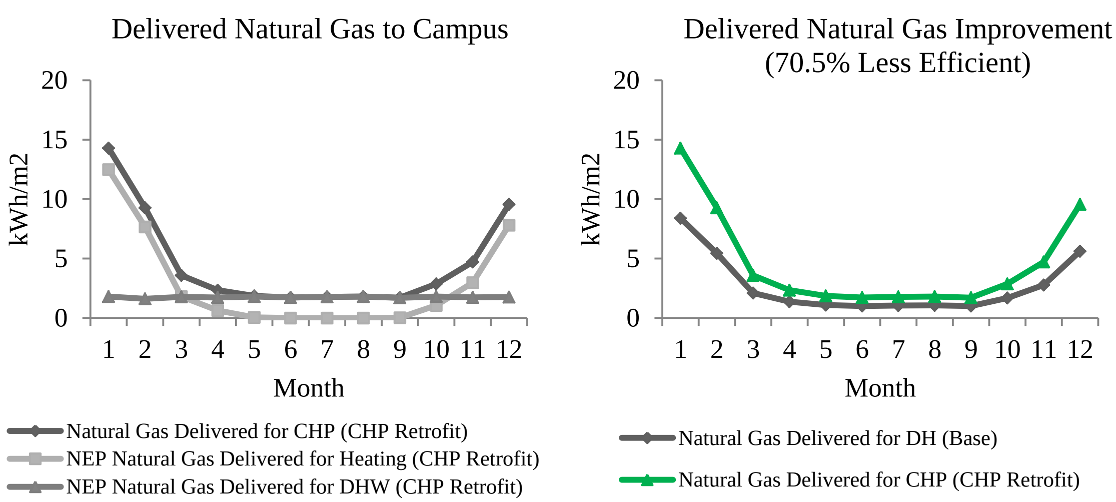
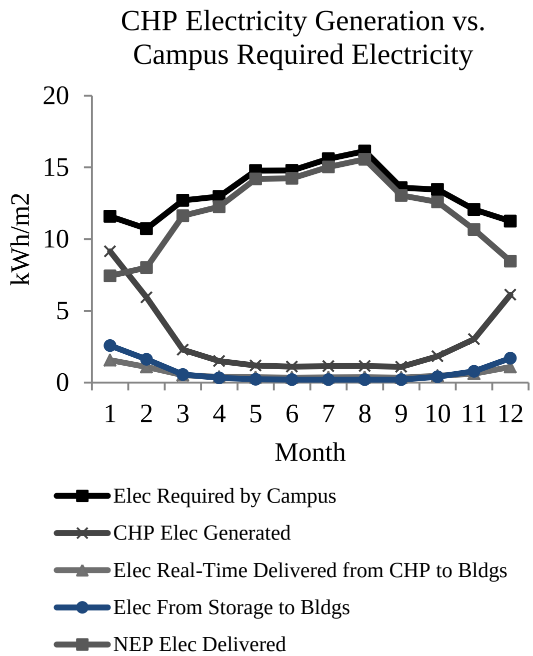
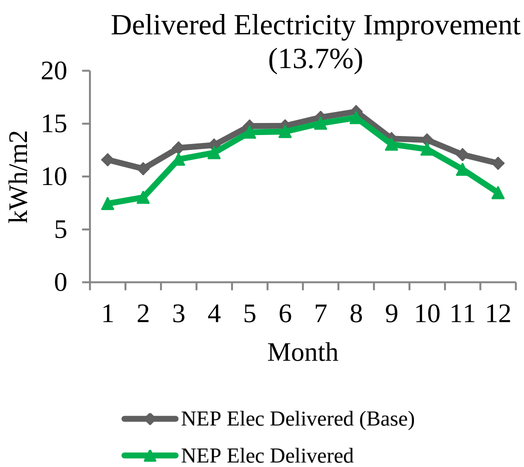


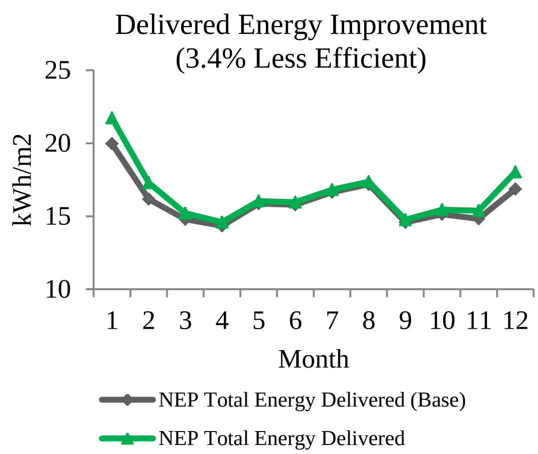
Figure 37 CHP Cogeneration Retrofit Scenario Modeling in NEP Dashboard

Figure 38 shows charts from the NEP calculation. The heat generation efficiency in the CHP is not as efficient as the boilers in the existing district heating plant. Thus, the CHP plant requires more natural gas delivered (70.5%) to the campus, but it generates electricity from the heat generation process, which reduces the electrical power demand (13.7%) from the grid. Although the retrofit scenario requires more natural gas, the reduced electricity demands contribute to reducing environmental impacts in primary energy (5.7%) and CO_2 emissions (5.9%). Figure 39 shows the moment when the electrical power demand peaks in summer. The generated electrical power contributes to reducing power delivery from the grid by 1.1%. Figure 40 shows the dynamics of electrical power generation, export, and storage for the hours when electrical power generation is greater than the demand from campus buildings. The retrofit scenario adds lead-acid batteries with efficiency of 0.72 to store the surplus after distributing electrical power to meet the hourly demand from the campus. The stored electricity is pulled out later, supporting the campus during hours when electricity demand is greater than generation.




CHP Electricity Generation vs.
Campus Required Electricity
kWh/m2
Month
Elec Required by Campus
CHP Elec Generated
Elec Real-Time Delivered from CHP to Bldgs
Elec From Storage to Bldgs
NEP Elec Delivered


Delivered Electricity Improvement
(13.7%)
kWh/m2
Month
NEP Elec Delivered (Base)
NEP Elec Delivered


Delivered Energy Improvement
(3.4% Less Efficient)
kWh/m2
Month
NEP Total Energy Delivered (Base)
NEP Total Energy Delivered

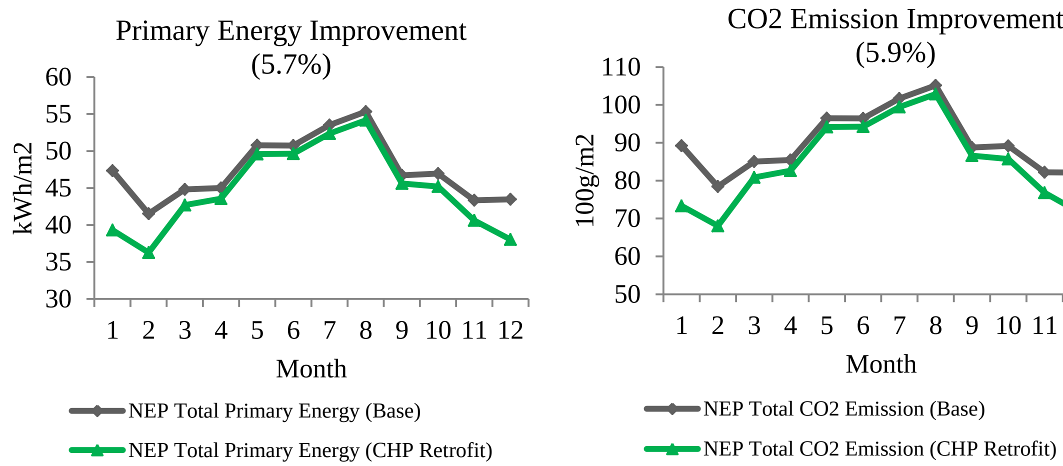


Figure 38 Campus Energy Savings from CHP Cogeneration Retrofit

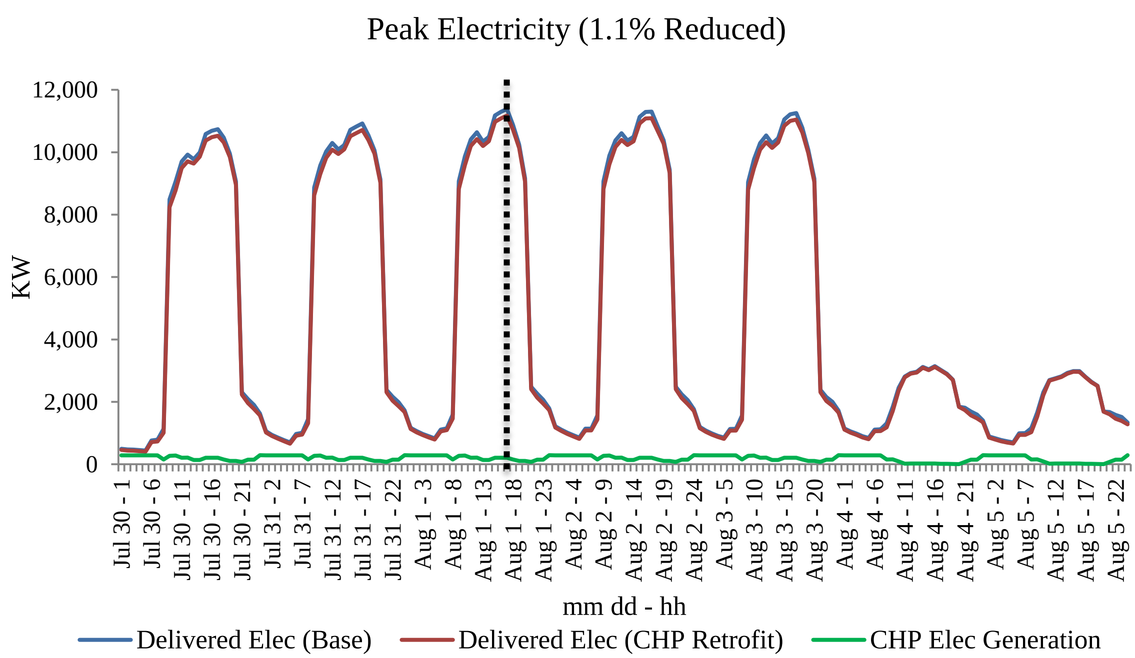


Figure 39 Peak Electricity Demand Reduction from CHP Cogeneration Retrofit

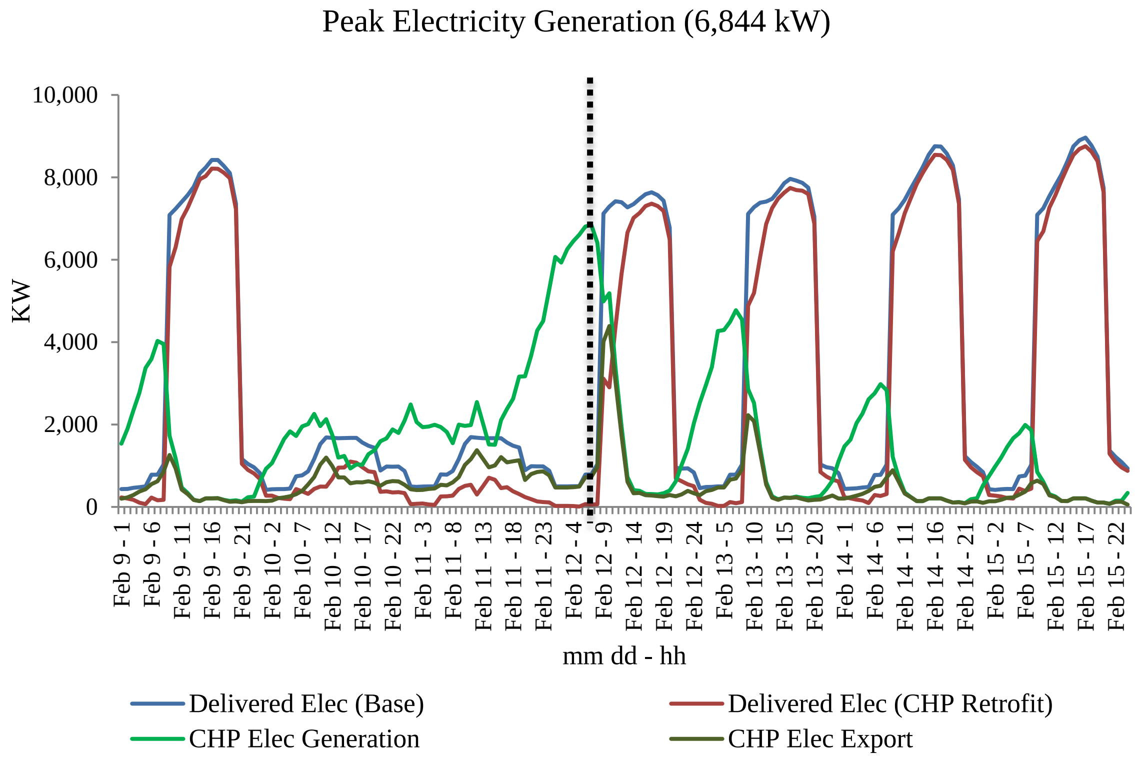


Figure 40 Electricity Demand from Campus Buildings, Electricity Generation by CHP and Export to Buildings during the Week Heating Load is the Greatest

4. Absorption Chillers in CHP Plant (from Scenario 3)
    - Absorption chillers COP: 1.0
    - Chiller water distribution to ten near buildings

The case study analyzed a trigeneration system in retrofit scenarios adding absorption chillers to the CHP plant. The CHP plant is capable of delivering chilled water as well as steam and produces electricity by burning natural gas. For the retrofit scenario, the capacity for all installed absorption chillers is 3,132kW meeting the peak cooling demand for ten buildings near the CHP plant. Still, the campus requires a district cooling plant to fully support the remaining cooling demand. Chillers in the district cooling plant have the same COP used in the baseline case. Typical absorption chillers in CHP plants are in the 0.7 – 1.7 COP range (EPA-NR, 2007; Harvey, 2006). Figure 41 shows buildings which are connected to different energy supply typologies on the campus. Figure 42 visualizes in the NEP dashboard the retrofit scenario model adding a trigeneration system for a different group of buildings.

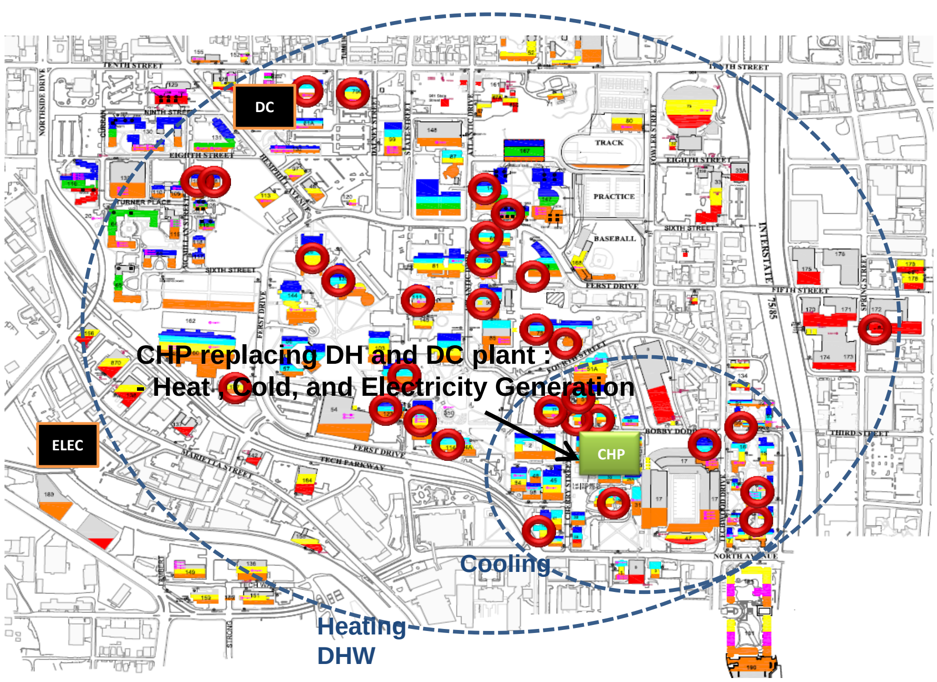


Figure 41 CHP Trigeneration Retrofit Impact to the Campus

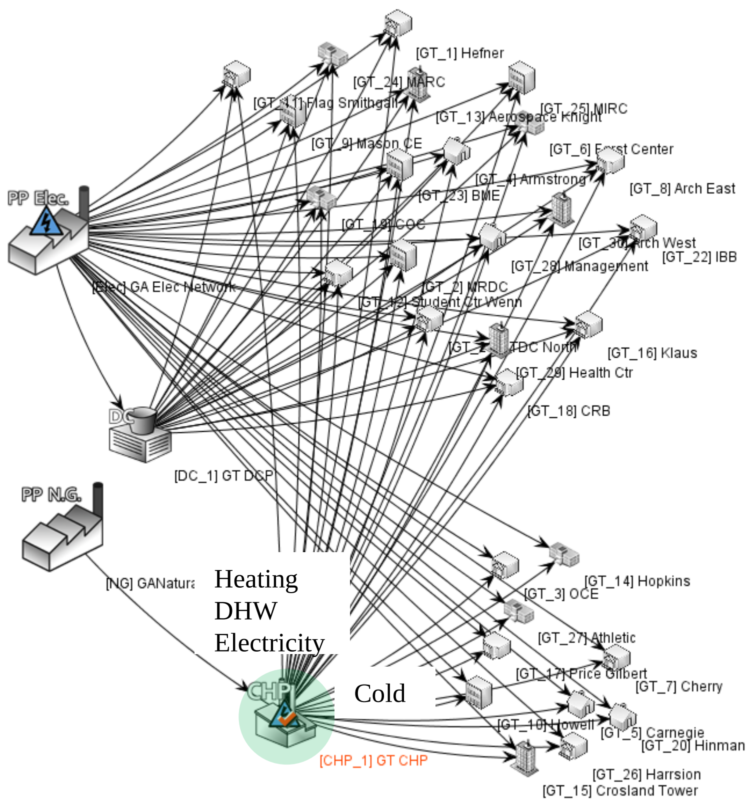
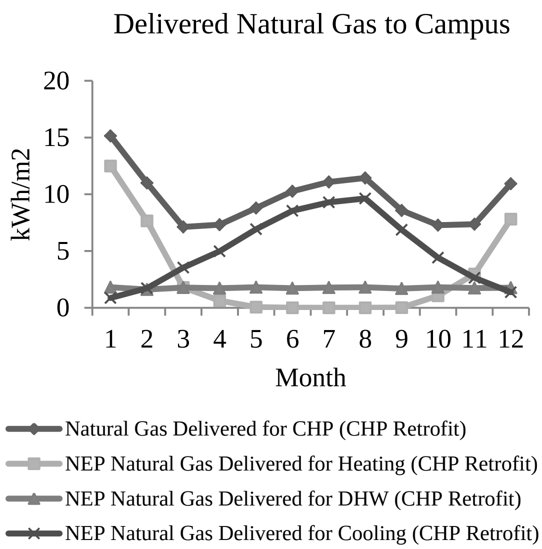
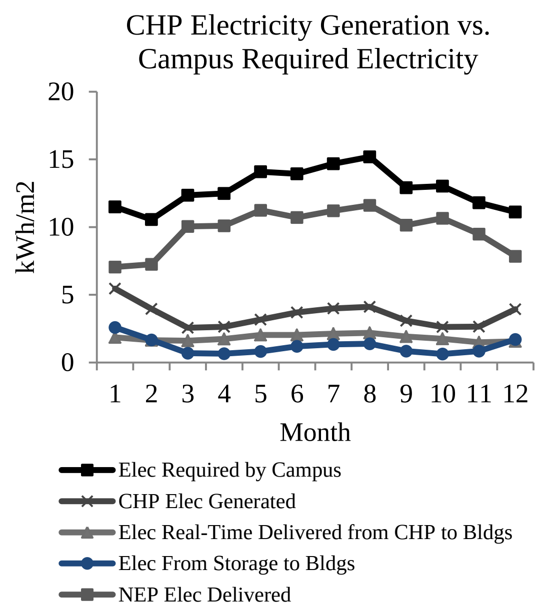
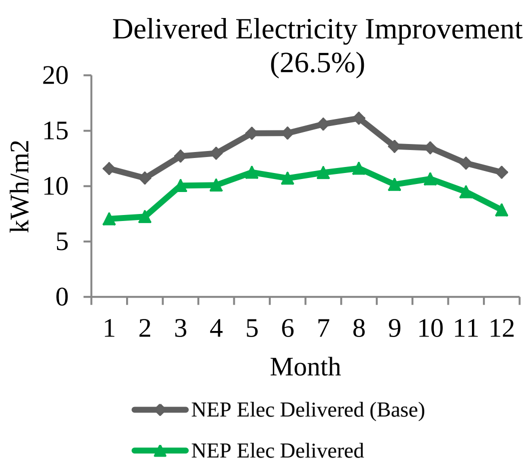


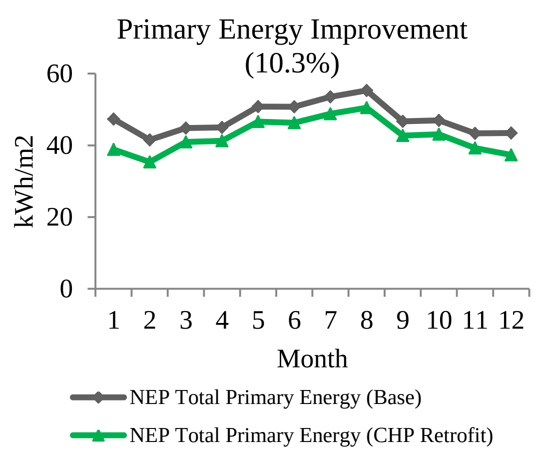
Figure 42 CHP Trigeneration Retrofit Scenario Modeling in NEP Dashboard

Charts in Figure 43 show the NEP calculation outcomes from the NEP hourly calculation displayed in a monthly format. As noted in the scenario 3, the CHP plant requires 70.5% more natural gas to meet heating and DHW demand. The cooling demand from ten networked buildings increases by 186.7% the natural gas requirement during the cooling season. However, ten buildings served by absorption chillers lighten the electricity demand. Electrically powered compression chillers in the district cooling plant have reduced cooling loads. Also, the natural gas burning process generating chilled water also generates electrical power in a local CHP plant. For hours when electrical energy generation is greater than demand, the surplus electrical power is stored in batteries. From the CHP trigeneration retrofit, the campus can reduce electrical energy by 26.5%, which reduces primary energy 10.3% and CO_2 emissions by 11.1% compared to the baseline case. Figure 44 shows electrical power reduction of 18.4% during the peak hour compared to the base case.









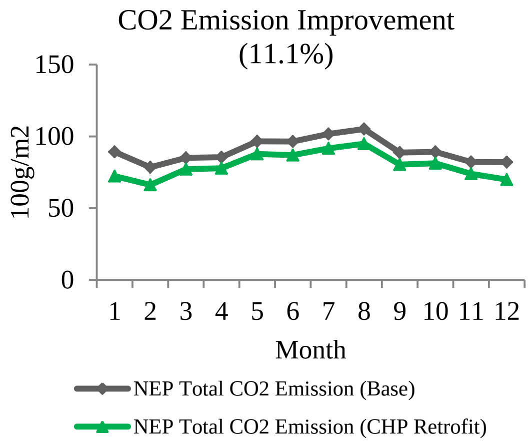


Figure 43 Campus Energy Savings from CHP Trigeneration Retrofit

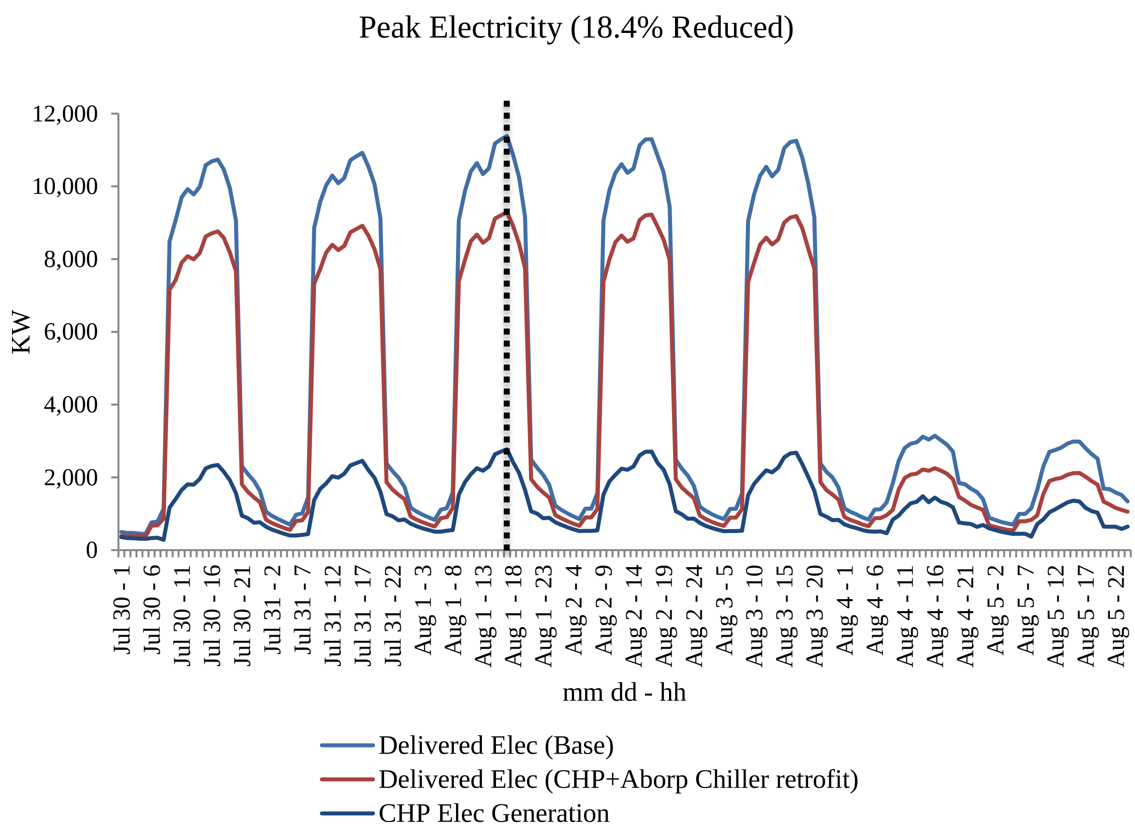


Figure 44 Peak Electricity Demand Reduction from CHP Trigeneration Retrofit

5. Solar PV Station Supporting Electric Energy for Campus Buildings and District Cooling Plant Chillers
    - PV module area: 20,000m^2
    - PV module type: Mono crystalline silicon with efficiency 0.15
    - Orientation: South
    - Angle: 30^0

The case study analyzed adding a PV station with a solar module area of 20,000m^2. The selected technology is a mono crystalline silicon with an efficiency 0.15 (CEN, 2007c). The PV panels are designed to be mounted at a fixed angle of 30^0 and oriented toward the south. The angle was determined considering that the optimal angle is equal or close to the latitude of the installation location when the angle is fixed throughout the year (Tiwari & Dubey, 2010). Figure 45 illustrates the PV station addition as a retrofit scenario to the campus and its energy supply typology impacts. Figure 46 visualizes the retrofit scenario model adding a PV station system for different group of buildings in the NEP dashboard.

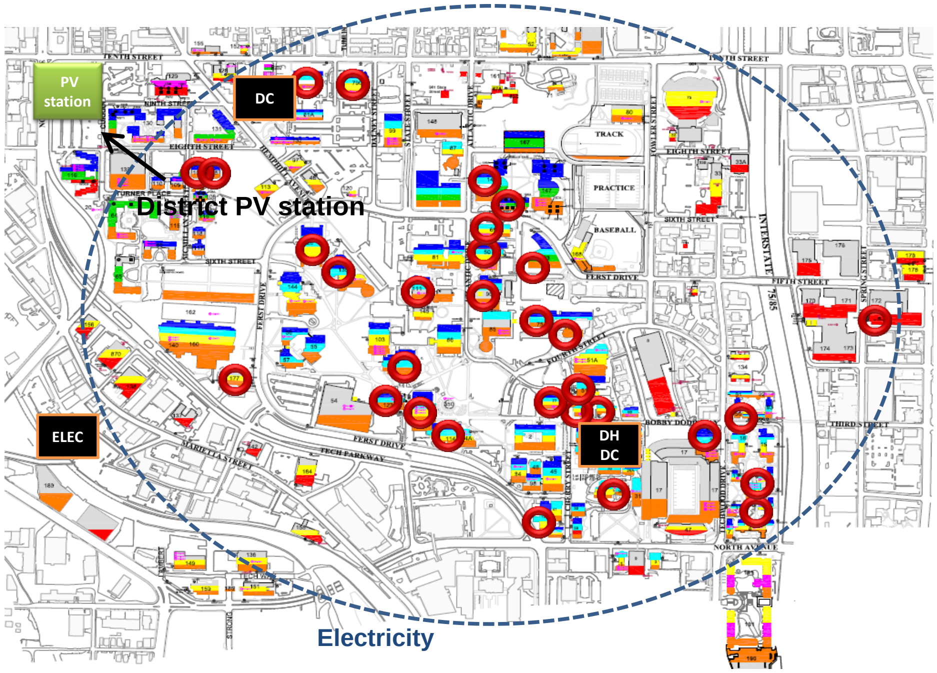


Figure 45 PV Station Retrofit Impact to the Campus

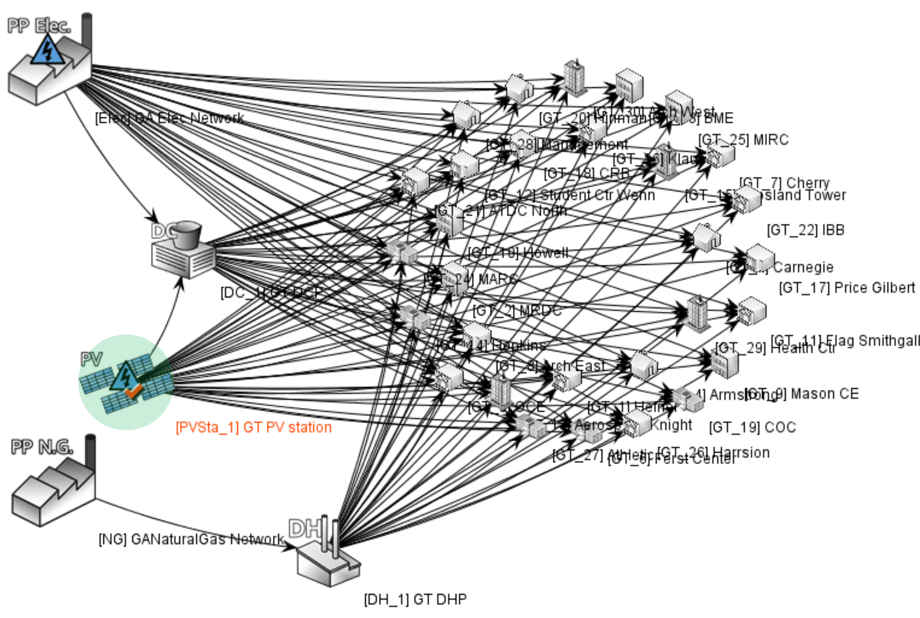
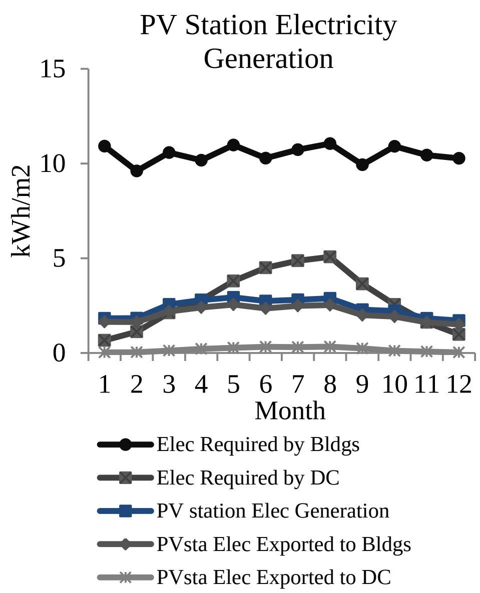
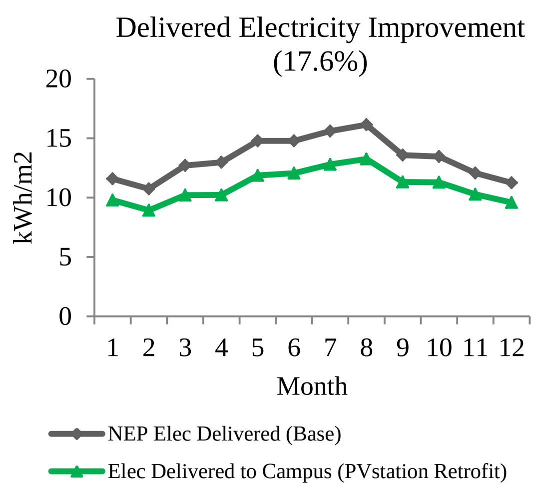


Figure 46 PV Station Retrofit Scenario Modeling in NEP Dashboard

The peak energy generation from the PV station occurs on April 25th at 2:00 p.m. when it is generating 3,339kW. The PV station addition reduces electricity delivery from the power grid on a campus scale by 17.8%. The generated electrical power can support the electrical energy requirements of the building auxiliary systems (15.6 %) and the district cooling plant (1.3%) during the daytime. The surplus energy generation is 0.9% per year total and is stored in batteries. Charts in Figure 47 show the NEP calculation outcomes. The PV station retrofit scenario contributes to reducing environmental impacts in primary energy (16.5%) and CO_2 emissions (16.6%). Figure 48 shows the hour when the electrical power demand from the campus peaks and the dynamics of energy generation and export from the PV station to the campus grid. The retrofit scenario contributes to a 7.1% reduction in grid-supplied electrical power at the peak hour.





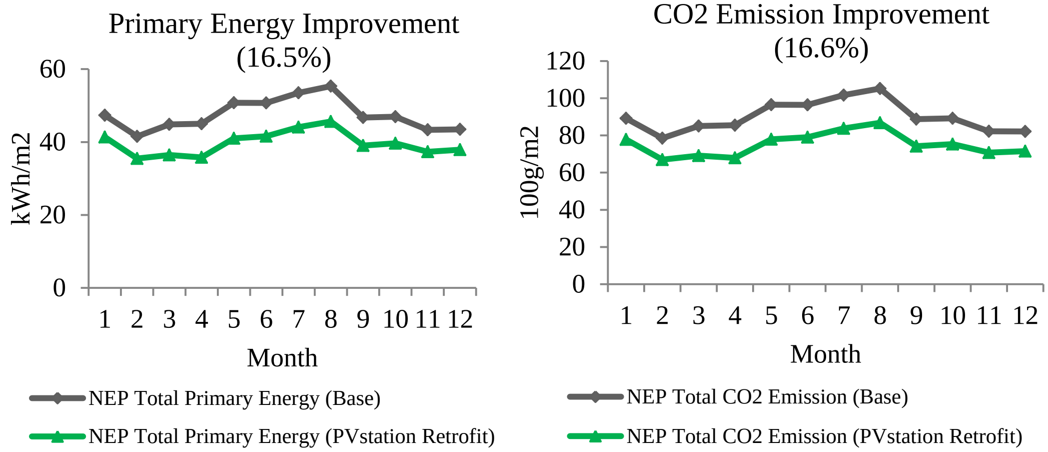


Figure 47 Campus Energy Savings from PV Station Retrofit

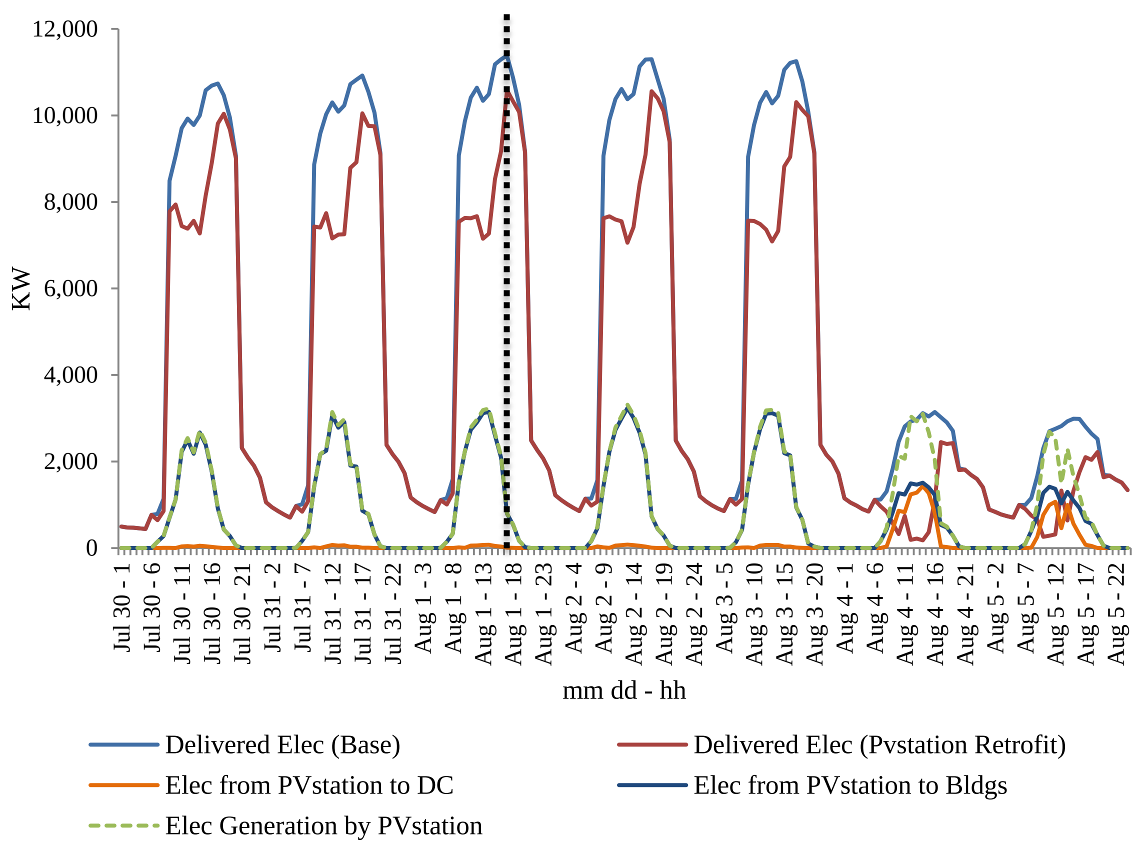


Figure 48 Peak Electricity Demand Reduction from PV Station Retrofit

6. Building Integrated PV Panel at Dormitories
    - Each dormitory exporting surplus electrical power to three buildings
    - BIPV module area: Dormitory building roof area
    - BIPV module type : Mono-crystalline silicon (efficiency 0.15)
    - Orientation: South
    - Angle: 30^0

Different building typologies support different building operations and functions. Dormitory buildings experience most of their major operations at night. By contrast most of other campus buildings are occupied during the daytime, and need rigorous management of their energy consuming systems to support their functions such as classrooms, offices, and laboratories. Solar energy generation from dormitory buildings can be used for energy supply to other buildings during energy generating hours. The selected technology is a mono-crystalline silicon with an efficiency of 0.15 (CEN, 2007c). The PV panel chosen for the analysis was designed with a fixed angle of 30^0 and an orientation toward the south, placed on the roof. The BIPV module area is the same as the roof area for each dormitory building. Figure 49 illustrates electricity demands from dormitory buildings and energy generation from the installed BIPV system. The chart shows that energy generation during daytime is greater than energy demand, which explains why it is useful for exporting surplus electricity to other buildings or for selling it back to the electricity power utility.

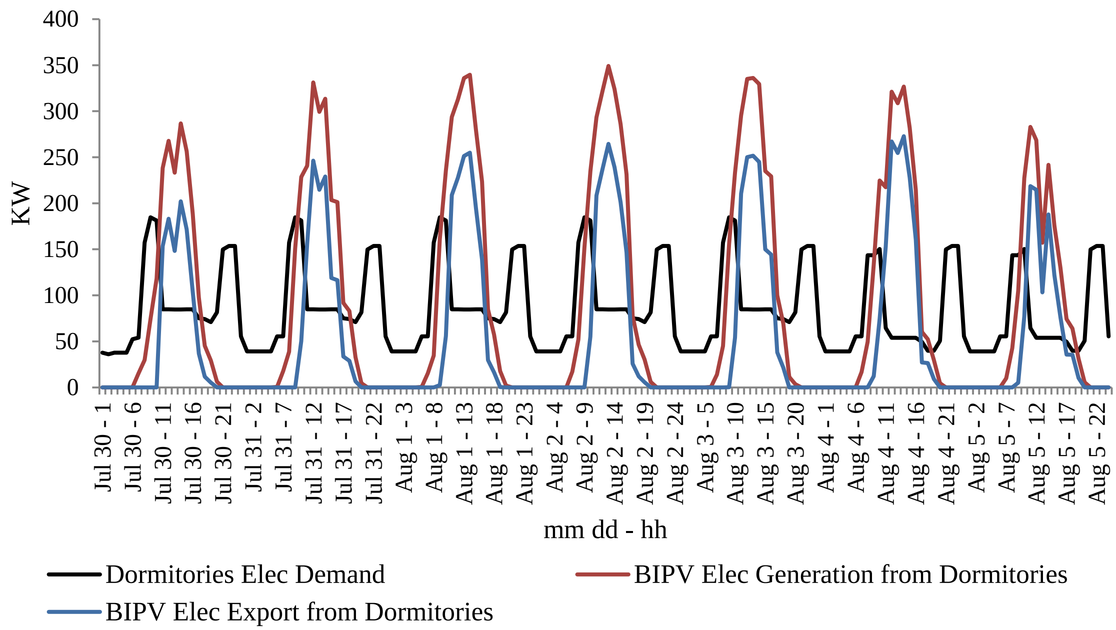


Figure 49 BIPV from Dormitory Buildings Electricity Generation and Export

Figure 50 illustrates five dormitory buildings (in the green circle) with BIPV modules and 15 buildings connected to the dormitory buildings. Figure 51 visualizes the retrofit scenario model, BIPV dormitory buildings exporting electricity to the selected buildings in the NEP dashboard.

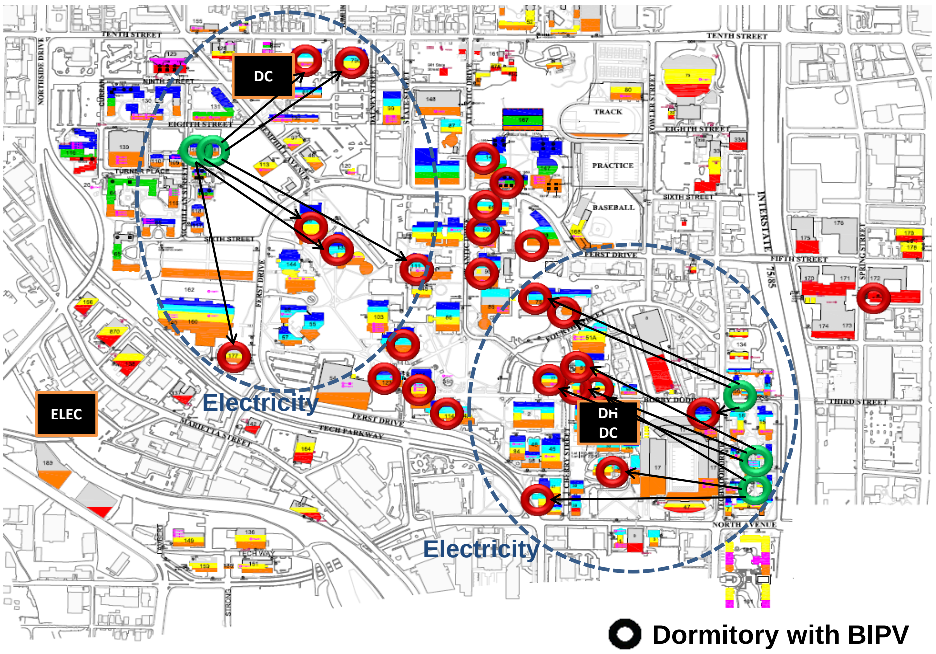


Figure 50 BIPV Retrofit on Dormitory Buildings Impact to the Campus

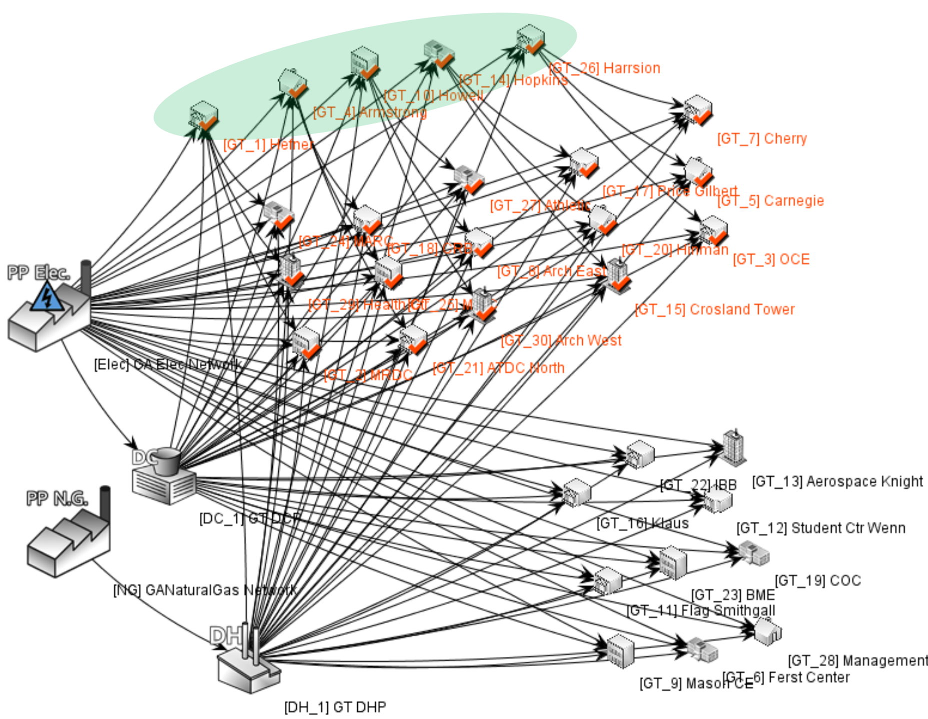
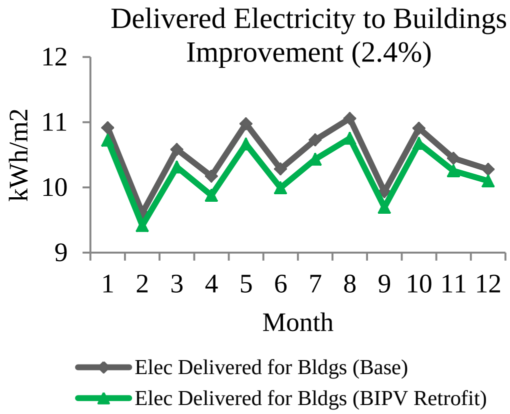
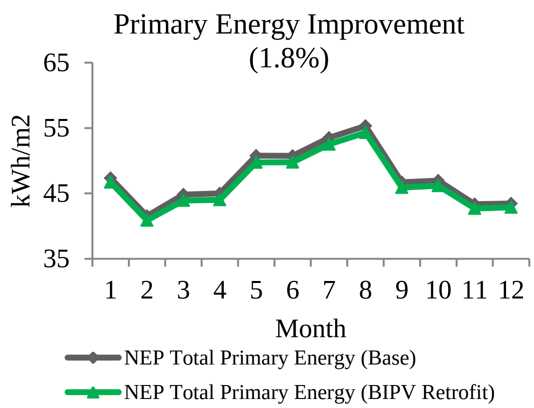


Figure 51 BIPV Retrofit on Dormitory Buildings Scenario Modeling in NEP Dashboard



Bldgs	Electricity Savings
Dormitories (Savings from BIPV generation)	40.1%
Other Buildings (Savings from exported electricity from dormitories)	1.4%
Total Campus	2.4%



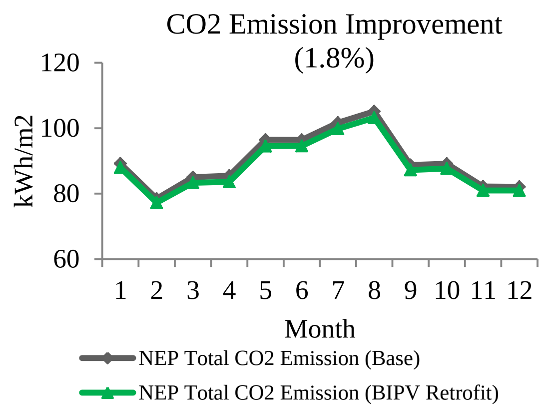


Figure 52 Campus Energy Savings from BIPV Retrofit on Dormitory Buildings

Peak Electricity (0.7% Reduced)

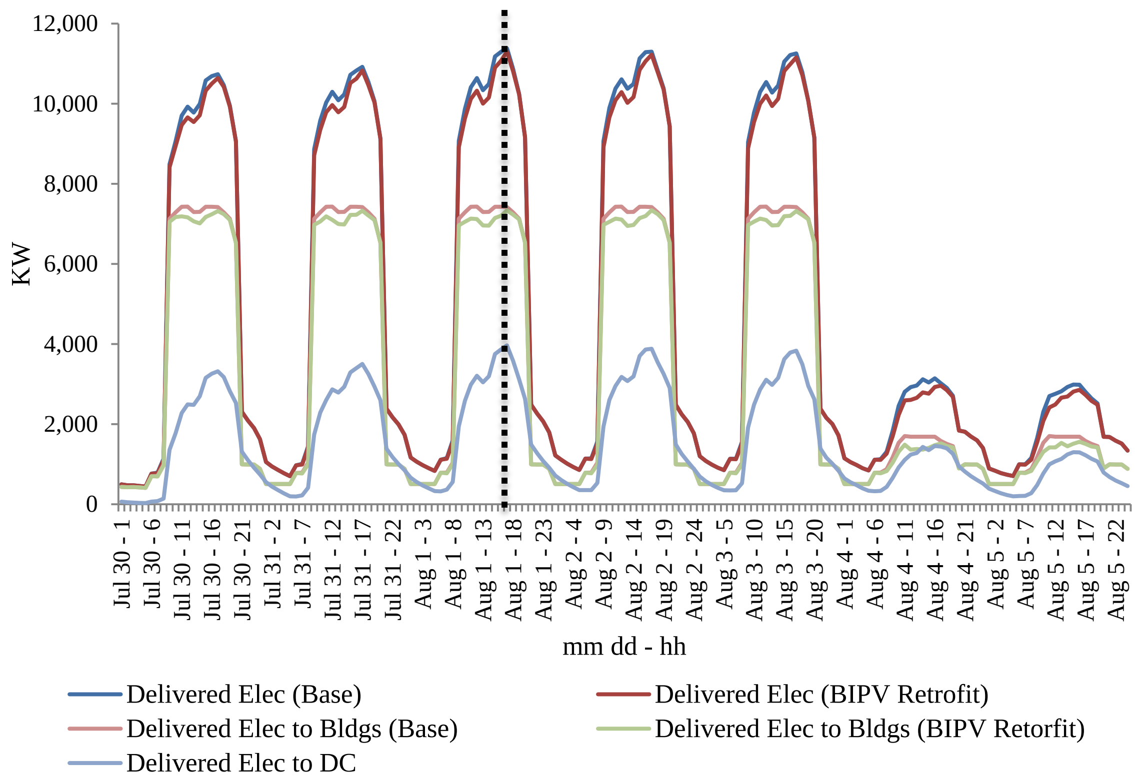


Figure 53 Peak Electricity Demand Reduction from PV Station Retrofit

Figure 52 shows the NEP calculation outcomes from the BIPV retrofit scenario which reveals electricity savings both in dormitories and other connected buildings. Generated power primarily meets the electrical demand from the BIPV installed buildings themselves, which reduces electrical demand by 40.1%. Then, the surplus power produced during energy generating hours is exported to the other buildings contributing 1.4% of the energy demand for those buildings. In this case study, five dormitory buildings are capable of exporting electrical power for 3,332 hours over the whole year. Overall savings are 2.4% on electricity consumption from the entire set of 30 buildings. This contributes reducing environmental impacts by 1.8% for primary energy and CO_2 emissions. Figure 53 shows the hour when the electrical power demand from the campus peaks in addition to the dynamics of energy generation and export from the BIPV system on dormitory buildings. The retrofit scenario contributes to a reduction of 0.7% in electrical power at the peak hour. The maximum electrical savings occurs on March 18th at 2:00 p.m. During this hour, 22% of electrical power demand can be reduced compared to the base case.

CHAPTER 6

CONCLUSIONS

This thesis explores a novel application for systematic energy performance assessment at a large-scale in the building sector. Taking advantage of a normative calculation method, the author developed the Network Energy Performance (NEP) model with accompanying NEP software, which enables analyzing the total environmental impacts at campus-scale or at the level of a corporate portfolio of structures. The NEP model uses the Energy Performance Standard Calculation Toolkit (EPSCT) as an underlying engine to calculate building energy performance. The merit of the NEP model is that it is capable of incorporating multiple energy suppliers and consumers into the assessment to cover a microcosm of the energy grid. The NEP is a lightweight tool that supports rapid decision making for energy efficient system design.

The development is based on the normative approach, which does not require a deep simulation, because the goal is macro design decisions not micro operational decisions. The premise of the NEP development was that energy performance assessment of each node based on a normative model is accurate enough to support macro decision making. The normative model uses the hourly calculation method to capture dynamic phenomena of thermal energy needs, delivered energy requirements for different activities in buildings, and available energy generation and surpluses, all analyzed in hourly time intervals. However, the heat balance module at a building level does not include latent heat load, which may lead to a structural weakness for a location where energy need for (de)humidification is significant. Although normative model is a best candidate as it is a right engineering approach for the large scale energy performance assessment, the current CEN-ISO calculation method may need to be recalibrated in every climate with local building types and technologies. The node for suppliers and energy flow connections need to capture dynamic contexts considering diverse conditions of supply system sizing and partial load efficiency, energy storage, and controls.

The distinguishing elements of the NEP method are that the assessment is scalable to larger portfolios and energy systems and both the energy suppliers and consumers are flexible so that the user can explore different topologies by adding or taking away nodes. The nodes and relationships between nodes are managed in a graphical interface based on the directed graph theory, defining the energy flow from suppliers to consumers. Robust underlying representations of the network have the ability to perform recalculations at any time. The time required by the NEP software for model construction and calculation time with the NEP software is exceedingly fast if it is compared to simulations. The calculation takes less than 0.3 seconds per node in average which enables supporting rapid decision making for the design of energy-efficient systems by evaluating different planning topologies integrating energy suppliers and consumers.

The thesis conducted a case study to test the hypothesis. Data representing energy suppliers and consumers (that latter consisting of 30 buildings) was collected from actual facilities on the Georgia Tech campus and each component system in the campus energy network was modeled and analyzed using both the NEP model method and a dynamic simulation method to test convenience in viability and optimality in decision making. The case study was demonstrated at Georgia Tech Facilities for evaluating viability of the NEP model approach in routine campus portfolio management, and convenience for macro system level decision making was substantiated by energy managers. Although base case study shows that the results from the NEP model are accurate enough compared with simulation results, no full-proof guarantees for optimal macro decision making with the NEP. Because, the validation should be done with uncertainty considered decision making.

This thesis presents a novel model and application for the systematic, fast, accurate energy performance quantification and demonstrates it on a microcosm of the energy grid. Large-scale energy performance assessment using the NEP model brings rich information resources to decision makers as they work to reduce environmental impacts and achieve energy savings at a district level in the building sector.

The NEP model development has just begun. It is expected that the NEP model and software will be used widely in practice anywhere that an energy efficient system design at a campus or portfolio scale is needed. The NEP model will help research areas related to the large-scale energy performance such as “campus energy retrofit decision making under uncertainty”, “campus energy performance rating”, and “real time energy control and management of the network”.

APPENDIX A

NEP INPUT TEMPLATE

Table 8 NEP Input Template: Building General and System

Class	Field	Description
buildingGeneral	bldg_id	Building id
buildingGeneral	bldg_name	Building name
buildingGeneral	terrain_class	Building location: select from reference table
buildingGeneral	bldg_volume	Building total ventilated volume (m3)
buildingGeneral	bldg_height	Building height (m)
buildingGeneral	bldg_mass_type	Building heat capacity (J/K/m2): select from reference table
buildingGeneral	t_set_heat_occ	Internal set point for heating for occupied period (deg C)
buildingGeneral	t_set_heat_unocc	Internal set point for heating for unoccupied period (deg C)
buildingGeneral	t_set_cool_occ	Internal set point for cooling for occupied period (deg C)
buildingGeneral	t_set_cool_unocc	Internal set point for cooling for unoccupied period (deg C)
buildingSystem	cool_cop	Cooling system coefficient of Performance (COP) (KW/KW)
buildingSystem	cool_plv	Cooling system mean Partial Load Value (PLV)
buildingSystem	heat_cop	Heating system coefficient of Performance (COP) (KW/KW)
buildingSystem	heat_plv	Heating system mean Partial Load Value (PLV)
buildingSystem	airflow_me_supply	Mechanical supply air flow rate (liter/s)
buildingSystem	heat_recov_eff	Heat recovery efficiency: refer to reference table
buildingSystem	exhaust_recirc_rate	Exhaust air recirculation rate (eg. 0.2: 20% recirculated)
buildingSystem	bldg_air_leakage	Building air leakage level under Q4Pa (m3/h/m2)
buildingSystem	pump_power	Specific installed electrical power of pumps for heating and cooling, in W/m2 (eg. typically in between 0.5 - 1.0)
buildingSystem	pump_ctrl_cool	Pump control for cooling: select from reference table
buildingSystem	pump_ctrl_heat	Pump control for heating: select from reference table
buildingSystem	dhw_distr_system_type	DHW distribution system: select from reference table
buildingSystem	dhw_gen_eff	DHW generation system efficiency

Table 9 NEP Input Template: Building Renewable, Roof, and Opaque Wall

Class	Field	Description
renewable	pv_module_surface_area	PV module surface area (m2)
renewable	pv_module_orientation	PV module orientation anlge (eg 0: S, -45: SE, -90: E, -135: NE, 180: N, 135: NW, 90: W, 45: SW)
renewable	pv_module_angle	PV module angle (eg 0: horizontal, 30: 30 degree)
renewable	pv_module_type	PV module type: select from reference table
renewable	pv_module_integration_type	PV module building integration type: select from reference table
renewable	shw_collector_area	solar collector surface area (m2)
renewable	shw_collector_orientation	SHW collector orientation (eg 0: S, -45: SE, -90: E, -135: NE, 180: N, 135: NW, 90: W, 45: SW)
renewable	shw_collector_angle	SHW collector angle (eg 0: horizontal, 30: 30 degree)
roof1	roof_op_area	Roof opaqgue area (m2)
roof1	roof_op_uValue	Roof opaque U-Value (W/m2/K)
roof1	roof_op_absor_coeff	Roof opaque area absorption coefficient
roof1	roof_op_emissivity	Roof oparque area emissivity
roof1	roof_gl_area	Roof glazing (skylight) area (m2)
roof1	roof_gl_uValue	Roof glazing U-Value (W/m2/K)
roof1	roof_gl_solar_trans	Roof glazing solar energy transmittance
roof1	roof_gl_emissivity	Roof glazing area emissivity
roof1	roof_gl_overhang_factor	Roof glazing overhang shading factor
roof1	roof_gl_fin_factor	Roof glazing fin shading factor
roof1	roof_gl_shading_device_factor	Roof glazing shading device factor
opaque1	op_uValue	Wall opaque U-Value by orientation (W/m2/K)
opaque1	op_absor_coeff	Wall opaque area absorption coefficient by orientation
opaque1	op_emissivity	Wall opaque area emissivity by orientation
opaque1	op_S_area	Wall opaque area by orientation South(m2)
opaque1	op_SE_area	Wall opaque area by orientation SouthEast (m2)
opaque1	op_E_area	Wall opaque area by orientation East (m2)
opaque1	op_NE_area	Wall opaque area by orientation NorthEast (m2)
opaque1	op_N_area	Wall opaque area by orientation North (m2)
opaque1	op_NW_area	Wall opaque area by orientation NorthWest (m2)
opaque1	op_W_area	Wall opaque area by orientation West (m2)
opaque1	op_SW_area	Wall opaque area by orientation SouthWest (m2)
opaque1	op_belowgrade_area	Wall opaque area by below grade (m2)

Table 10 NEP Input Template: Building Glazing

Class	Field	Description
glazing1	gl_uValue	Wall glazing U-Value by orientation (W/m2/K)
glazing1	gl_solar_trans	Wall glazing solar energy transmittance
glazing1	gl_emissivity	Wall glazing area emissivity
glazing1	gl_S_area	Wall glazing area by orientation South (m2)
glazing1	gl_SE_area	Wall glazing area by orientation SouthEast (m2)
glazing1	gl_E_area	Wall glazing area by orientation East (m2)
glazing1	gl_NE_area	Wall glazing area by orientation NorthEast (m2)
glazing1	gl_N_area	Wall glazing area by orientation North (m2)
glazing1	gl_NW_area	Wall glazing area by orientation NorthWest(m2)
glazing1	gl_W_area	Wall glazing area by orientation West (m2)
glazing1	gl_SW_area	Wall glazing area by orientation SouthWest (m2)
glazing1	gl_S_overhang_factor	Wall glazing overhang shading factor by orientation South
glazing1	gl_SE_overhang_factor	Wall glazing overhang shading factor by orientation SouthEast
glazing1	gl_E_overhang_factor	Wall glazing overhang shading factor by orientation East
glazing1	gl_NE_overhang_factor	Wall glazing overhang shading factor by orientation NorthEast
glazing1	gl_N_overhang_factor	Wall glazing overhang shading factor by orientation North
glazing1	gl_NW_overhang_factor	Wall glazing overhang shading factor by orientation NorthWest
glazing1	gl_W_overhang_factor	Wall glazing overhang shading factor by orientation West
glazing1	gl_SW_overhang_factor	Wall glazing overhang shading factor by orientation SouthWest
glazing1	gl_S_fin_factor	Wall glazing fin shading factor by orientation South
glazing1	gl_SE_fin_factor	Wall glazing fin shading factor by orientation SouthEast
glazing1	gl_E_fin_factor	Wall glazing fin shading factor by orientation East
glazing1	gl_NE_fin_factor	Wall glazing fin shading factor by orientation NorthEast
glazing1	gl_N_fin_factor	Wall glazing fin shading factor by orientation North
glazing1	gl_NW_fin_factor	Wall glazing fin shading factor by orientation NorthWest
glazing1	gl_W_fin_factor	Wall glazing fin shading factor by orientation West
glazing1	gl_SW_fin_factor	Wall glazing fin shading factor by orientation SouthWest
glazing1	gl_S_shading_device_factor	Wall glazing shading device factor by orientation South
glazing1	gl_SE_shading_device_factor	Wall glazing shading device factor by orientation SouthEast
glazing1	gl_E_shading_device_factor	Wall glazing shading device factor by orientation East
glazing1	gl_NE_shading_device_factor	Wall glazing shading device factor by orientation NorthEast
glazing1	gl_N_shading_device_factor	Wall glazing shading device factor by orientation North
glazing1	gl_NW_shading_device_factor	Wall glazing shading device factor by orientation NorthWest
glazing1	gl_W_shading_device_factor	Wall glazing shading device factor by orientation West
glazing1	gl_SW_shading_device_factor	Wall glazing shading device factor by orientation SouthWest

Table 11 NEP Input Template: Building Glazing

Class	Field	Description
zone1	zone_type	Zone Name
zone1	zone_area	Conditioned floor area with internal dimension (m2)
zone1	zone_occ_density	Occupant density (m2/person)
zone1	zone_occ_metabolic_rate	Metabolic rate (W/person)
zone1	zone_app_heat_flow_rate	Appliance (w/m2)
zone1	zone_light_heat_flow_rate	Lighting power intensity (W/m2)
zone1	zone_light_daylight_factor	Lighting daylighting factor
zone1	zone_light_occ_factor	Lighting occupancy sensor factor
zone1	zone_light_constant_factor	Lighting constant illumination control factor
zone1	zone_freshair_per_occ	Outside air flow rate for occupied period (liter/s/person)
zone1	zone_dhw	DHW use (liter/m2/day)
zone1	zone_vent_type	Ventilation type: select from reference table
zone1	zone_fan_opeartion_type	Fan operation type: select from reference table
zone1	zone_demand_ctrl_type	Unoccupied period fresh air supply control type
zone1	zone_nv_window_open_area	If natural ventilation is used, window area totally opened (m2)
zone1	zone_nv_window_open_angle_type	If natural ventilation, angle of opening for bottom hung window: select from reference table

APPENDIX B

GEORGIA TECH CASE STUDY 30 BUILDINGS

Table 12 Georgia Tech Selected 30 Buildings

Bldg_Id	GT Bldg #	Bldg Name	Space (Zone)	Construction Type	Built Year	Major Renovation Year	GSF
GT_1	107	HEFNER	Dormitory	Steel or concrete	1969	1997	24,130
GT_2	135	MRDC	Office, Classroom, Lab, Light industry, Storage, Computer Lab	Steel or concrete	1995		121,973
GT_3	58	OLD CIVIL ENG	Office, Lab, Classroom, Light Industry	Steel or concrete	1939	2008	33,434
GT_4	108	ARMSTRONG	Dormitory	Steel or concrete	1969	1997	22,460
GT_5	36	Carnegie	Office	Heavy timber or laminate	1906	1954	10,221
GT_6	124	Ferst Center	Office, Theatre Storage, Meeting Room, Theater Stage	Steel or concrete	1992		38,213
GT_7	66	Cherry	Office, Lab	Steel or concrete	1959		15,579
GT_8	76	Arch East	Office, Classroom, Light Industry, auditorium	Steel or concrete	1952		61,962
GT_9	111	MASON (CE)	Office, Lab, Classroom, Computer Lab, Mech. Room, Hallway	Steel or concrete	1969		93,576
GT_10	10	Howell	Office, Mech. Room, Hallway, Dormitory	Steel or concrete	1939	1999	23933
GT_11	123	Flag Smithgall	Office, Lounge, Hallway, Mech. Room	Steel or concrete	1990		42598
GT_12	114	Student Center	Fitness, Office, Hallway, Conference, Lounge, Kitchen, Restaurant, Computer Lab, Theater Stage	Steel or concrete	1970	2004	21956
GT_13	101	Knight	Hallway, Lab, Lounge, Office, Storage	Steel or concrete	1968		55409
GT_14	94	Hopkins	Hallway, Storage, Laundry, Dormitory, Shower Bath, Lounge	Steel or concrete	1961	1995	24,403
GT_15	100	CrosLand Tower	Hallway, Storage, Office, Library, Conference	Steel or concrete	1953		99,832
GT_16	153	Klaus	Class Room, Hallway, Storage, Lab, Lounge, Office, Conference, Computer Lab, Mech.	Steel or concrete	2006		417,576

			Room				
GT_17	77	Price Gilbert	Hallway, Office, Library, Mech. Room, Storage	Steel or concrete	1953		99,832
GT_18	790	C.R.B.	Hallway, Office, Conference, Mech. Room, Storage, Lab	Steel or concrete	1984		197,981
GT_19	50	COC	Hallway, Office, Conference, Mech. Room, Storage, Lab	Steel or concrete	1989		118,217
GT_20	51	Hinman	Hallway, Office, Computer Lab, Mech. Room	Steel or concrete	1939	2001	17,910
GT_21	61	ATDC North	Hallway, Office, Conference, Lab, Storage, Mech. Room	Steel or concrete	1983		46,678
GT_22	146	IBB	Hallway, Office, Light Industry, Lab, Mech. Room	Steel or concrete	1999		155,767
GT_23	165	BME	Hallway, Office, Lab, Mech. Room, Computer Lab, Lounge, Classroom	Steel or concrete	2002		99,822
GT_24	126	MARC	Hallway, Office, Lab, Mech. Room, Storage, Conference	Steel or concrete	1990		118,250
GT_25	95	MIRC - Petit	Hallway, Office, Lab, Mech. Room, Storage, Conference, Classroom, Computer Lab, Lounge	Steel or concrete	1988		98,420
GT_26	14	HARRISON	Hallway, Kitchen, Shower, Mech. Room, Dormitory, Lounge	Steel or concrete	1939	1998	30,526
GT_27	18	Edge Athletic center	Hallway, Office, Kitchen, Mech. Room, Conference, Eating, Lounge, Shower, Medical, Gym	Steel or concrete	1982		72,775
GT_28	172	Management	Hallway, Office, Retail, Classroom, Conference, Lounge	Steel or concrete	2001		264,432
GT_29	177	Health Center	Hallway, Office, Medical, Mech. Room	Steel or concrete	2002		38,750
GT_30	75	Arch West	Hallway, Office, Lounge, Lab, Library	Steel or concrete	1980		52,724

APPENDIX C

SPACE TYPES AND INTERNAL ACTIVITY DATA

C.1 Space Types and Activities Information for the Georgia Tech Case Study

Table 13 Defined Space Type and Standardized Data for Internal Activity Data

Name	1 Office	2 Class Room	3 Lab	4 Computer Lab	5 Storage	6 Hallway	7 Light Industry	8 Dormitory
Occupancy (m2/person)	14.29	5.00	9.09	5.00	9.09	9.09	50.00	10.00
Metabolic rate (W/person)	120	140	160	120	140	140	250	100
Appliance (w/m2)	10.0	2.0	10.0	30.0	2.0	2.0	50.0	5.0
Lighting (W/m2)	25.0	15.0	40.0	15.0	2.5	5.0	50.0	8.0
Outdoor Air (lter/s/person)	10.0	10.0	12.0	10.0	10.0	10.0	10.0	10.0
DHW (liter/m2/month)	2.9	2.3	4.5	7.8	0.0	0.0	0.0	196.5

Name	9 Theater Office	10 Theater Storage	11 Theater Meeting Room	12 Theater Stage	13 Lounge	14 Food Preparation	15 Eat & Drink	16 Gym
Occupancy (m2/person)	14.29	9.09	5.00	20.00	9.09	9.09	5.00	5.88
Metabolic rate (W/person)	120	140	120	250	100	180	110	300
Appliance (w/m2)	10.0	2.0	5.0	2.0	5.0	40.0	20.0	15.0
Lighting (W/m2)	25.0	2.5	15.0	37.5	15.0	50.0	15.0	15.0
Outdoor Air (liter/s/person)	10.0	10.0	10.0	10.0	10.0	17.5	10.0	30.0
DHW (liter/m2/month)	6.3	0.0	1.8	0.0	0.0	5.4	101.3	0.0

Name	17 Conference	18 Laundry	19 Shower	20 Library	21 Mechanical Room	22 Medical Office	23 Retail
Occupancy (m2/person)	5.00	9.09	5.00	5.00	9.09	5.00	9.09
Metabolic rate (W/person)	120	180	120	180	180	140	140
Appliance (w/m2)	5.0	50.0	2.0	5.0	50.0	42.8	5.0
Lighting (W/m2)	30.0	30.0	15.0	20.0	20.0	40.0	60.0
Outdoor Air (liter/s/person)	10.0	12.0	12.0	10.0	10.0	10.0	10.0
DHW (liter/m2/month)	0.9	0.0	0.0	2.3	0.0	0.0	0.0

C.2 Internal Activity Schedule Used for the Georgia Tech Case Study

Table 14 Internal Heat Gain Source Schedule for the Space Type Used in the Georgia Tech Case Study

1 Office						
Hour	Occ _WD	Occ _WE	Equi _WD	Equi _WE	Light _WD	Light _WE
1	0.00	0.00	0.05	0.05	0.00	0.00
2	0.00	0.00	0.05	0.05	0.00	0.00
3	0.00	0.00	0.05	0.05	0.00	0.00
4	0.00	0.00	0.05	0.05	0.00	0.00
5	0.00	0.00	0.05	0.05	0.00	0.00
6	0.00	0.00	0.05	0.05	0.00	0.00
7	0.00	0.00	0.05	0.05	0.00	0.00
8	0.00	0.00	0.05	0.05	0.00	0.00
9	0.50	0.00	1.00	0.05	1.00	0.00
10	1.00	0.00	1.00	0.05	1.00	0.00
11	1.00	0.00	1.00	0.05	1.00	0.00
12	1.00	0.00	1.00	0.05	1.00	0.00
13	0.50	0.00	1.00	0.05	1.00	0.00
14	0.50	0.00	1.00	0.05	1.00	0.00
15	1.00	0.00	1.00	0.05	1.00	0.00
16	1.00	0.00	1.00	0.05	1.00	0.00
17	1.00	0.00	1.00	0.05	1.00	0.00
18	0.75	0.00	1.00	0.05	1.00	0.00
19	0.50	0.00	1.00	0.05	1.00	0.00
20	0.50	0.00	1.00	0.05	1.00	0.00
21	0.00	0.00	0.05	0.05	0.00	0.00
22	0.00	0.00	0.05	0.05	0.00	0.00
23	0.00	0.00	0.05	0.05	0.00	0.00
24	0.00	0.00	0.05	0.05	0.00	0.00

2 Classroom						
Hour	Occ _WD	Occ _WE	Equi _WD	Equi _WE	Light _WD	Light _WE
1	0.00	0.00	0.05	0.05	0.00	0.00
2	0.00	0.00	0.05	0.05	0.00	0.00
3	0.00	0.00	0.05	0.05	0.00	0.00
4	0.00	0.00	0.05	0.05	0.00	0.00
5	0.00	0.00	0.05	0.05	0.00	0.00
6	0.00	0.00	0.05	0.05	0.00	0.00
7	0.00	0.00	0.05	0.05	0.00	0.00
8	0.00	0.00	0.05	0.05	0.00	0.00
9	0.50	0.00	1.00	0.05	1.00	0.00
10	1.00	0.00	1.00	0.05	1.00	0.00
11	1.00	0.00	1.00	0.05	1.00	0.00
12	1.00	0.00	1.00	0.05	1.00	0.00
13	0.50	0.00	1.00	0.05	1.00	0.00
14	0.50	0.00	1.00	0.05	1.00	0.00
15	1.00	0.00	1.00	0.05	1.00	0.00
16	1.00	0.00	1.00	0.05	1.00	0.00
17	1.00	0.00	1.00	0.05	1.00	0.00
18	0.75	0.00	1.00	0.05	1.00	0.00
19	0.50	0.00	1.00	0.05	1.00	0.00
20	0.50	0.00	1.00	0.05	1.00	0.00
21	0.00	0.00	0.05	0.05	0.00	0.00
22	0.00	0.00	0.05	0.05	0.00	0.00
23	0.00	0.00	0.05	0.05	0.00	0.00
24	0.00	0.00	0.05	0.05	0.00	0.00

Table 15 Internal Heat Gain Source Schedule for the Space Type Used in the Georgia Tech Case Study (Continued)

3 Lab						
Hour	Occ _WD	Occ _WE	Equi _WD	Equi _WE	Light _WD	Light _WE
1	0.00	0.00	0.05	0.05	0.00	0.00
2	0.00	0.00	0.05	0.05	0.00	0.00
3	0.00	0.00	0.05	0.05	0.00	0.00
4	0.00	0.00	0.05	0.05	0.00	0.00
5	0.00	0.00	0.05	0.05	0.00	0.00
6	0.00	0.00	0.05	0.05	0.00	0.00
7	0.00	0.00	0.05	0.05	0.00	0.00
8	0.00	0.00	0.05	0.05	0.00	0.00
9	0.50	0.00	1.00	0.05	1.00	0.00
10	1.00	0.00	1.00	0.05	1.00	0.00
11	1.00	0.00	1.00	0.05	1.00	0.00
12	1.00	0.00	1.00	0.05	1.00	0.00
13	0.50	0.00	1.00	0.05	1.00	0.00
14	0.50	0.00	1.00	0.05	1.00	0.00
15	1.00	0.00	1.00	0.05	1.00	0.00
16	1.00	0.00	1.00	0.05	1.00	0.00
17	1.00	0.00	1.00	0.05	1.00	0.00
18	0.75	0.00	1.00	0.05	1.00	0.00
19	0.50	0.00	1.00	0.05	1.00	0.00
20	0.50	0.00	1.00	0.05	1.00	0.00
21	0.00	0.00	0.05	0.05	0.00	0.00
22	0.00	0.00	0.05	0.05	0.00	0.00
23	0.00	0.00	0.05	0.05	0.00	0.00
24	0.00	0.00	0.05	0.05	0.00	0.00

4 Computer Lab						
Hour	Occ _WD	Occ _WE	Equi _WD	Equi _WE	Light _WD	Light _WE
1	0.00	0.00	0.05	0.05	0.00	0.00
2	0.00	0.00	0.05	0.05	0.00	0.00
3	0.00	0.00	0.05	0.05	0.00	0.00
4	0.00	0.00	0.05	0.05	0.00	0.00
5	0.00	0.00	0.05	0.05	0.00	0.00
6	0.00	0.00	0.05	0.05	0.00	0.00
7	0.00	0.00	0.05	0.05	0.00	0.00
8	0.00	0.00	0.05	0.05	0.00	0.00
9	0.25	0.00	1.00	0.05	1.00	0.00
10	0.75	0.00	1.00	0.05	1.00	0.00
11	1.00	0.00	1.00	0.05	1.00	0.00
12	1.00	0.00	1.00	0.05	1.00	0.00
13	0.75	0.00	1.00	0.05	1.00	0.00
14	0.75	0.00	1.00	0.05	1.00	0.00
15	1.00	0.00	1.00	0.05	1.00	0.00
16	1.00	0.00	1.00	0.05	1.00	0.00
17	1.00	0.00	1.00	0.05	1.00	0.00
18	0.75	0.00	1.00	0.05	1.00	0.00
19	0.50	0.00	1.00	0.05	1.00	0.00
20	0.50	0.00	1.00	0.05	1.00	0.00
21	0.00	0.00	0.05	0.05	0.00	0.00
22	0.00	0.00	0.05	0.05	0.00	0.00
23	0.00	0.00	0.05	0.05	0.00	0.00
24	0.00	0.00	0.05	0.05	0.00	0.00

Table 16 Internal Heat Gain Source Schedule for the Space Type Used in the Georgia Tech Case Study (Continued)

5 Storage						
Hour	Occ _WD	Occ _WE	Equi _WD	Equi _WE	Light _WD	Light _WE
1	0.00	0.00	0.05	0.05	0.00	0.00
2	0.00	0.00	0.05	0.05	0.00	0.00
3	0.00	0.00	0.05	0.05	0.00	0.00
4	0.00	0.00	0.05	0.05	0.00	0.00
5	0.00	0.00	0.05	0.05	0.00	0.00
6	0.00	0.00	0.05	0.05	0.00	0.00
7	0.00	0.00	0.05	0.05	0.00	0.00
8	0.00	0.00	0.05	0.05	0.00	0.00
9	0.05	0.00	1.00	0.05	1.00	0.00
10	0.05	0.00	1.00	0.05	1.00	0.00
11	0.05	0.00	1.00	0.05	1.00	0.00
12	0.05	0.00	1.00	0.05	1.00	0.00
13	0.05	0.00	1.00	0.05	1.00	0.00
14	0.05	0.00	1.00	0.05	1.00	0.00
15	0.05	0.00	1.00	0.05	1.00	0.00
16	0.05	0.00	1.00	0.05	1.00	0.00
17	0.05	0.00	1.00	0.05	1.00	0.00
18	0.05	0.00	1.00	0.05	1.00	0.00
19	0.05	0.00	1.00	0.05	1.00	0.00
20	0.05	0.00	1.00	0.05	1.00	0.00
21	0.00	0.00	0.05	0.05	0.00	0.00
22	0.00	0.00	0.05	0.05	0.00	0.00
23	0.00	0.00	0.05	0.05	0.00	0.00
24	0.00	0.00	0.05	0.05	0.00	0.00

6 Hallway						
Hour	Occ _WD	Occ _WE	Equi _WD	Equi _WE	Light _WD	Light _WE
1	0.00	0.00	0.05	0.05	0.00	0.00
2	0.00	0.00	0.05	0.05	0.00	0.00
3	0.00	0.00	0.05	0.05	0.00	0.00
4	0.00	0.00	0.05	0.05	0.00	0.00
5	0.00	0.00	0.05	0.05	0.00	0.00
6	0.00	0.00	0.05	0.05	0.00	0.00
7	0.00	0.00	0.05	0.05	0.00	0.00
8	0.00	0.00	0.05	0.05	0.00	0.00
9	0.25	0.00	1.00	0.05	1.00	0.00
10	0.25	0.00	1.00	0.05	1.00	0.00
11	0.25	0.00	1.00	0.05	1.00	0.00
12	0.25	0.00	1.00	0.05	1.00	0.00
13	0.25	0.00	1.00	0.05	1.00	0.00
14	0.25	0.00	1.00	0.05	1.00	0.00
15	0.25	0.00	1.00	0.05	1.00	0.00
16	0.25	0.00	1.00	0.05	1.00	0.00
17	0.25	0.00	1.00	0.05	1.00	0.00
18	0.10	0.00	1.00	0.05	1.00	0.00
19	0.10	0.00	1.00	0.05	1.00	0.00
20	0.10	0.00	1.00	0.05	1.00	0.00
21	0.00	0.00	0.05	0.05	0.00	0.00
22	0.00	0.00	0.05	0.05	0.00	0.00
23	0.00	0.00	0.05	0.05	0.00	0.00
24	0.00	0.00	0.05	0.05	0.00	0.00

Table 17 Internal Heat Gain Source Schedule for the Space Type Used in the Georgia Tech Case Study (Continued)

7 Light Industry						
Hour	Occ _WD	Occ _WE	Equi _WD	Equi _WE	Light _WD	Light _WE
1	0.00	0.00	0.05	0.05	0.00	0.00
2	0.00	0.00	0.05	0.05	0.00	0.00
3	0.00	0.00	0.05	0.05	0.00	0.00
4	0.00	0.00	0.05	0.05	0.00	0.00
5	0.00	0.00	0.05	0.05	0.00	0.00
6	0.00	0.00	0.05	0.05	0.00	0.00
7	0.00	0.00	0.05	0.05	0.00	0.00
8	0.00	0.00	0.05	0.05	0.00	0.00
9	0.50	0.00	1.00	0.05	1.00	0.00
10	1.00	0.00	1.00	0.05	1.00	0.00
11	1.00	0.00	1.00	0.05	1.00	0.00
12	1.00	0.00	1.00	0.05	1.00	0.00
13	0.50	0.00	1.00	0.05	1.00	0.00
14	0.50	0.00	1.00	0.05	1.00	0.00
15	1.00	0.00	1.00	0.05	1.00	0.00
16	1.00	0.00	1.00	0.05	1.00	0.00
17	1.00	0.00	1.00	0.05	1.00	0.00
18	0.75	0.00	1.00	0.05	1.00	0.00
19	0.50	0.00	1.00	0.05	1.00	0.00
20	0.50	0.00	1.00	0.05	1.00	0.00
21	0.00	0.00	0.05	0.05	0.00	0.00
22	0.00	0.00	0.05	0.05	0.00	0.00
23	0.00	0.00	0.05	0.05	0.00	0.00
24	0.00	0.00	0.05	0.05	0.00	0.00

8 Dormitory						
Hour	Occ _WD	Occ _WE	Equi _WD	Equi _WE	Light _WD	Light _WE
1	1.00	1.00	0.05	0.05	0.00	0.00
2	1.00	1.00	0.05	0.05	0.00	0.00
3	1.00	1.00	0.05	0.05	0.00	0.00
4	1.00	1.00	0.05	0.05	0.00	0.00
5	1.00	1.00	0.05	0.05	0.00	0.00
6	1.00	1.00	0.05	0.05	0.00	0.00
7	1.00	1.00	0.05	0.05	0.00	0.00
8	0.50	0.50	1.00	1.00	1.00	1.00
9	0.50	0.50	1.00	1.00	1.00	1.00
10	0.25	0.25	1.00	1.00	1.00	1.00
11	0.00	0.00	0.05	0.05	0.00	0.00
12	0.00	0.00	0.05	0.05	0.00	0.00
13	0.00	0.00	0.05	0.05	0.00	0.00
14	0.00	0.00	0.05	0.05	0.00	0.00
15	0.00	0.00	0.05	0.05	0.00	0.00
16	0.00	0.00	0.05	0.05	0.00	0.00
17	0.00	0.00	0.05	0.05	0.00	0.00
18	0.00	0.00	0.05	0.05	0.00	0.00
19	0.00	0.00	0.05	0.05	0.00	0.00
20	0.00	0.00	0.05	0.05	0.00	0.00
21	0.25	0.25	1.00	1.00	1.00	1.00
22	0.50	0.50	1.00	1.00	1.00	1.00
23	0.50	0.50	1.00	1.00	1.00	1.00
24	1.00	1.00	0.05	0.05	0.00	0.00

Table 18 Internal Heat Gain Source Schedule for the Space Type Used in the Georgia Tech Case Study (Continued)

9 Theater Office						
Hour	Occ _WD	Occ _WE	Equi _WD	Equi _WE	Light _WD	Light _WE
1	0.00	0.00	0.05	0.05	0.00	0.00
2	0.00	0.00	0.05	0.05	0.00	0.00
3	0.00	0.00	0.05	0.05	0.00	0.00
4	0.00	0.00	0.05	0.05	0.00	0.00
5	0.00	0.00	0.05	0.05	0.00	0.00
6	0.00	0.00	0.05	0.05	0.00	0.00
7	0.00	0.00	0.05	0.05	0.00	0.00
8	0.00	0.00	0.05	0.05	0.00	0.00
9	0.00	0.00	0.05	0.05	0.00	0.00
10	0.25	0.25	1.00	1.00	1.00	1.00
11	0.50	0.50	1.00	1.00	1.00	1.00
12	0.50	0.50	1.00	1.00	1.00	1.00
13	0.50	0.50	1.00	1.00	1.00	1.00
14	0.50	0.50	1.00	1.00	1.00	1.00
15	0.50	0.50	1.00	1.00	1.00	1.00
16	0.50	0.50	1.00	1.00	1.00	1.00
17	0.50	0.50	1.00	1.00	1.00	1.00
18	0.25	0.25	1.00	1.00	1.00	1.00
19	0.10	0.10	1.00	1.00	1.00	1.00
20	0.10	0.10	1.00	1.00	1.00	1.00
21	0.10	0.10	1.00	1.00	1.00	1.00
22	0.00	0.00	0.05	0.05	0.00	0.00
23	0.00	0.00	0.05	0.05	0.00	0.00
24	0.00	0.00	0.05	0.05	0.00	0.00

10 Theater Storage						
Hour	Occ _WD	Occ _WE	Equi _WD	Equi _WE	Light _WD	Light _WE
1	0.00	0.00	0.05	0.05	0.00	0.00
2	0.00	0.00	0.05	0.05	0.00	0.00
3	0.00	0.00	0.05	0.05	0.00	0.00
4	0.00	0.00	0.05	0.05	0.00	0.00
5	0.00	0.00	0.05	0.05	0.00	0.00
6	0.00	0.00	0.05	0.05	0.00	0.00
7	0.00	0.00	0.05	0.05	0.00	0.00
8	0.00	0.00	0.05	0.05	0.00	0.00
9	0.00	0.00	0.05	0.05	0.00	0.00
10	0.05	0.05	1.00	1.00	1.00	1.00
11	0.05	0.05	1.00	1.00	1.00	1.00
12	0.05	0.05	1.00	1.00	1.00	1.00
13	0.05	0.05	1.00	1.00	1.00	1.00
14	0.05	0.05	1.00	1.00	1.00	1.00
15	0.05	0.05	1.00	1.00	1.00	1.00
16	0.05	0.05	1.00	1.00	1.00	1.00
17	0.05	0.05	1.00	1.00	1.00	1.00
18	0.05	0.05	1.00	1.00	1.00	1.00
19	0.05	0.05	1.00	1.00	1.00	1.00
20	0.00	0.00	0.05	0.05	0.00	0.00
21	0.00	0.00	0.05	0.05	0.00	0.00
22	0.00	0.00	0.05	0.05	0.00	0.00
23	0.00	0.00	0.05	0.05	0.00	0.00
24	0.00	0.00	0.05	0.05	0.00	0.00

Table 19 Internal Heat Gain Source Schedule for the Space Type Used in the Georgia Tech Case Study (Continued)

11 Theater Meeting Room						
Hour	Occ _WD	Occ _WE	Equi _WD	Equi _WE	Light _WD	Light _WE
1	0.00	0.00	0.05	0.05	0.00	0.00
2	0.00	0.00	0.05	0.05	0.00	0.00
3	0.00	0.00	0.05	0.05	0.00	0.00
4	0.00	0.00	0.05	0.05	0.00	0.00
5	0.00	0.00	0.05	0.05	0.00	0.00
6	0.00	0.00	0.05	0.05	0.00	0.00
7	0.00	0.00	0.05	0.05	0.00	0.00
8	0.00	0.00	0.05	0.05	0.00	0.00
9	0.00	0.00	0.05	0.05	0.00	0.00
10	0.25	0.25	1.00	1.00	1.00	1.00
11	0.25	0.25	1.00	1.00	1.00	1.00
12	0.25	0.25	1.00	1.00	1.00	1.00
13	0.25	0.25	1.00	1.00	1.00	1.00
14	0.25	0.25	1.00	1.00	1.00	1.00
15	0.25	0.25	1.00	1.00	1.00	1.00
16	0.25	0.25	1.00	1.00	1.00	1.00
17	0.25	0.25	1.00	1.00	1.00	1.00
18	0.00	0.00	0.05	0.05	0.00	0.00
19	0.00	0.00	0.05	0.05	0.00	0.00
20	0.00	0.00	0.05	0.05	0.00	0.00
21	0.00	0.00	0.05	0.05	0.00	0.00
22	0.00	0.00	0.05	0.05	0.00	0.00
23	0.00	0.00	0.05	0.05	0.00	0.00
24	0.00	0.00	0.05	0.05	0.00	0.00

12 Theater Stage						
Hour	Occ _WD	Occ _WE	Equi _WD	Equi _WE	Light _WD	Light _WE
0	0.00	0.00	0.05	0.05	0.00	0.00
2	0.00	0.00	0.05	0.05	0.00	0.00
3	0.00	0.00	0.05	0.05	0.00	0.00
4	0.00	0.00	0.05	0.05	0.00	0.00
5	0.00	0.00	0.05	0.05	0.00	0.00
6	0.00	0.00	0.05	0.05	0.00	0.00
7	0.00	0.00	0.05	0.05	0.00	0.00
8	0.00	0.00	0.05	0.05	0.00	0.00
9	0.00	0.00	0.05	0.05	0.00	0.00
10	0.00	0.00	0.05	0.05	0.00	0.00
11	0.20	0.20	1.00	1.00	1.00	1.00
12	0.20	0.20	1.00	1.00	1.00	1.00
13	0.20	0.20	1.00	1.00	1.00	1.00
14	0.50	0.50	1.00	1.00	1.00	1.00
15	0.50	0.50	1.00	1.00	1.00	1.00
16	0.50	0.50	1.00	1.00	1.00	1.00
17	0.50	0.50	1.00	1.00	1.00	1.00
18	0.75	0.75	1.00	1.00	1.00	1.00
19	0.75	0.75	1.00	1.00	1.00	1.00
20	0.75	0.75	1.00	1.00	1.00	1.00
21	0.75	0.75	1.00	1.00	1.00	1.00
22	0.75	0.75	1.00	1.00	1.00	1.00
23	0.75	0.75	1.00	1.00	1.00	1.00
24	0.75	0.75	1.00	1.00	1.00	1.00

Table 20 Internal Heat Gain Source Schedule for the Space Type Used in the Georgia Tech Case Study (Continued)

13 Lounge						
Hour	Occ _WD	Occ _WE	Equi _WD	Equi _WE	Light _WD	Light _WE
1	0.00	0.00	0.25	0.25	0.00	0.00
2	0.00	0.00	0.25	0.25	0.00	0.00
3	0.00	0.00	0.25	0.25	0.00	0.00
4	0.00	0.00	0.25	0.25	0.00	0.00
5	0.00	0.00	0.25	0.25	0.00	0.00
6	0.00	0.00	0.25	0.25	0.00	0.00
7	0.00	0.00	0.25	0.25	0.00	0.00
8	0.10	0.00	1.00	0.25	1.00	0.00
9	0.25	0.00	1.00	0.25	1.00	0.00
10	0.25	0.00	1.00	0.25	1.00	0.00
11	0.10	0.00	1.00	0.25	1.00	0.00
12	0.10	0.00	1.00	0.25	1.00	0.00
13	0.25	0.00	1.00	0.25	1.00	0.00
14	0.25	0.00	1.00	0.25	1.00	0.00
15	0.10	0.00	1.00	0.25	1.00	0.00
16	0.10	0.00	1.00	0.25	1.00	0.00
17	0.10	0.00	1.00	0.25	1.00	0.00
18	0.10	0.00	1.00	0.25	1.00	0.00
19	0.00	0.00	0.25	0.25	0.00	0.00
20	0.00	0.00	0.25	0.25	0.00	0.00
21	0.00	0.00	0.25	0.25	0.00	0.00
22	0.00	0.00	0.25	0.25	0.00	0.00
23	0.00	0.00	0.25	0.25	0.00	0.00
24	0.00	0.00	0.25	0.25	0.00	0.00

14 Food Preparation						
Hour	Occ _WD	Occ _WE	Equi _WD	Equi _WE	Light _WD	Light _WE
1	0.00	0.00	0.05	0.05	0.00	0.00
2	0.00	0.00	0.05	0.05	0.00	0.00
3	0.00	0.00	0.05	0.05	0.00	0.00
4	0.00	0.00	0.05	0.05	0.00	0.00
5	0.00	0.00	0.05	0.05	0.00	0.00
6	0.00	0.00	0.05	0.05	0.00	0.00
7	0.00	0.00	0.05	0.05	0.00	0.00
8	0.00	0.00	0.05	0.05	0.00	0.00
9	0.00	0.00	0.05	0.05	0.00	0.00
10	0.00	0.00	0.05	0.05	0.00	0.00
11	0.50	0.10	1.00	1.00	1.00	1.00
12	1.00	0.25	1.00	1.00	1.00	1.00
13	1.00	0.25	1.00	1.00	1.00	1.00
14	1.00	0.25	1.00	1.00	1.00	1.00
15	0.50	0.25	1.00	1.00	1.00	1.00
16	0.50	0.25	1.00	1.00	1.00	1.00
17	0.50	0.00	1.00	0.05	1.00	0.00
18	0.75	0.00	1.00	0.05	1.00	0.00
19	0.50	0.00	1.00	0.05	1.00	0.00
20	0.50	0.00	1.00	0.05	1.00	0.00
21	0.00	0.00	0.05	0.05	0.00	0.00
22	0.00	0.00	0.05	0.05	0.00	0.00
23	0.00	0.00	0.05	0.05	0.00	0.00
24	0.00	0.00	0.05	0.05	0.00	0.00

Table 21 Internal Heat Gain Source Schedule for the Space Type Used in the Georgia Tech Case Study (Continued)

15 Eat & Drink						
Hour	Occ _WD	Occ _WE	Equi _WD	Equi _WE	Light _WD	Light _WE
1	0.00	0.00	0.05	0.05	0.00	0.00
2	0.00	0.00	0.05	0.05	0.00	0.00
3	0.00	0.00	0.05	0.05	0.00	0.00
4	0.00	0.00	0.05	0.05	0.00	0.00
5	0.00	0.00	0.05	0.05	0.00	0.00
6	0.00	0.00	0.05	0.05	0.00	0.00
7	0.00	0.00	0.05	0.05	0.00	0.00
8	0.00	0.00	0.05	0.05	0.00	0.00
9	0.25	0.00	0.05	0.05	0.00	0.00
10	0.50	0.00	0.05	0.05	0.00	0.00
11	0.50	0.10	1.00	1.00	1.00	1.00
12	1.00	0.20	1.00	1.00	1.00	1.00
13	1.00	0.50	1.00	1.00	1.00	1.00
14	1.00	0.50	1.00	1.00	1.00	1.00
15	0.50	0.20	1.00	1.00	1.00	1.00
16	0.50	0.10	1.00	1.00	1.00	1.00
17	0.50	0.10	1.00	1.00	1.00	1.00
18	0.75	0.00	1.00	0.05	0.00	0.00
19	0.50	0.00	1.00	0.05	0.00	0.00
20	0.50	0.00	1.00	0.05	0.00	0.00
21	0.00	0.00	0.05	0.05	0.00	0.00
22	0.00	0.00	0.05	0.05	0.00	0.00
23	0.00	0.00	0.05	0.05	0.00	0.00
24	0.00	0.00	0.05	0.05	0.00	0.00

16 Gym						
Hour	Occ _WD	Occ _WE	Equi _WD	Equi _WE	Light _WD	Light _WE
1	0.00	0.00	0.05	0.05	0.00	0.00
2	0.00	0.00	0.05	0.05	0.00	0.00
3	0.00	0.00	0.05	0.05	0.00	0.00
4	0.00	0.00	0.05	0.05	0.00	0.00
5	0.00	0.00	0.05	0.05	0.00	0.00
6	0.00	0.00	0.05	0.05	0.00	0.00
7	0.00	0.00	0.05	0.05	0.00	0.00
8	0.00	0.00	0.05	0.05	0.00	0.00
9	0.50	0.00	1.00	0.05	1.00	0.00
10	1.00	0.75	1.00	1.00	1.00	1.00
11	1.00	0.75	1.00	1.00	1.00	1.00
12	1.00	0.75	1.00	1.00	1.00	1.00
13	0.50	0.50	1.00	1.00	1.00	1.00
14	0.50	0.50	1.00	1.00	1.00	1.00
15	1.00	0.75	1.00	1.00	1.00	1.00
16	1.00	0.75	1.00	1.00	1.00	1.00
17	1.00	0.75	1.00	1.00	1.00	1.00
18	0.75	0.75	1.00	1.00	1.00	1.00
19	0.75	0.00	1.00	0.05	1.00	0.00
20	0.75	0.00	1.00	0.05	1.00	0.00
21	0.00	0.00	0.05	0.05	0.00	0.00
22	0.00	0.00	0.05	0.05	0.00	0.00
23	0.00	0.00	0.05	0.05	0.00	0.00
24	0.00	0.00	0.05	0.05	0.00	0.00

Table 22 Internal Heat Gain Source Schedule for the Space Type Used in the Georgia Tech Case Study (Continued)

17 Conference						
Hour	Occ _WD	Occ _WE	Equi _WD	Equi _WE	Light _WD	Light _WE
1	0.00	0.00	0.05	0.05	0.00	0.00
2	0.00	0.00	0.05	0.05	0.00	0.00
3	0.00	0.00	0.05	0.05	0.00	0.00
4	0.00	0.00	0.05	0.05	0.00	0.00
5	0.00	0.00	0.05	0.05	0.00	0.00
6	0.00	0.00	0.05	0.05	0.00	0.00
7	0.00	0.00	0.05	0.05	0.00	0.00
8	0.00	0.00	0.05	0.05	0.00	0.00
9	0.50	0.00	1.00	0.05	1.00	0.00
10	1.00	0.00	1.00	0.05	1.00	0.00
11	1.00	0.00	1.00	0.05	1.00	0.00
12	1.00	0.00	1.00	0.05	1.00	0.00
13	0.50	0.00	1.00	0.05	1.00	0.00
14	0.50	0.00	1.00	0.05	1.00	0.00
15	1.00	0.00	1.00	0.05	1.00	0.00
16	1.00	0.00	1.00	0.05	1.00	0.00
17	1.00	0.00	1.00	0.05	1.00	0.00
18	0.75	0.00	1.00	0.05	1.00	0.00
19	0.50	0.00	1.00	0.05	1.00	0.00
20	0.50	0.00	1.00	0.05	1.00	0.00
21	0.00	0.00	0.05	0.05	0.00	0.00
22	0.00	0.00	0.05	0.05	0.00	0.00
23	0.00	0.00	0.05	0.05	0.00	0.00
24	0.00	0.00	0.05	0.05	0.00	0.00

18 Laundry						
Hour	Occ _WD	Occ _WE	Equi _WD	Equi _WE	Light _WD	Light _WE
1	0.00	0.00	0.05	0.05	0.00	0.00
2	0.00	0.00	0.05	0.05	0.00	0.00
3	0.00	0.00	0.05	0.05	0.00	0.00
4	0.00	0.00	0.05	0.05	0.00	0.00
5	0.00	0.00	0.05	0.05	0.00	0.00
6	0.00	0.00	0.05	0.05	0.00	0.00
7	0.00	0.00	0.05	0.05	0.00	0.00
8	0.00	0.00	0.05	0.05	0.00	0.00
9	0.00	0.00	0.05	0.05	0.00	0.00
10	0.00	0.00	0.05	0.05	0.00	0.00
11	0.05	0.15	1.00	1.00	1.00	1.00
12	0.05	0.15	1.00	1.00	1.00	1.00
13	0.05	0.15	1.00	1.00	1.00	1.00
14	0.05	0.15	1.00	1.00	1.00	1.00
15	0.05	0.15	1.00	1.00	1.00	1.00
16	0.05	0.15	1.00	1.00	1.00	1.00
17	0.00	0.15	0.05	1.00	0.00	1.00
18	0.00	0.00	0.05	0.05	0.00	0.00
19	0.00	0.00	0.05	0.05	0.00	0.00
20	0.00	0.00	0.05	0.05	0.00	0.00
21	0.00	0.00	0.05	0.05	0.00	0.00
22	0.00	0.00	0.05	0.05	0.00	0.00
23	0.00	0.00	0.05	0.05	0.00	0.00
24	0.00	0.00	0.05	0.05	0.00	0.00

Table 23 Internal Heat Gain Source Schedule for the Space Type Used in the Georgia Tech Case Study (Continued)

19 Shower						
Hour	Occ _WD	Occ _WE	Equi _WD	Equi _WE	Light _WD	Light _WE
1	0.00	0.00	0.05	0.05	0.00	0.00
2	0.00	0.00	0.05	0.05	0.00	0.00
3	0.00	0.00	0.05	0.05	0.00	0.00
4	0.00	0.00	0.05	0.05	0.00	0.00
5	0.00	0.00	0.05	0.05	0.00	0.00
6	0.00	0.00	0.05	0.05	0.00	0.00
7	0.00	0.00	0.05	0.05	0.00	0.00
8	0.50	0.50	1.00	0.05	1.00	0.00
9	0.50	0.50	1.00	0.05	1.00	0.00
10	0.50	0.50	1.00	1.00	1.00	1.00
11	0.00	0.00	0.05	1.00	0.00	1.00
12	0.00	0.00	0.05	0.05	0.00	0.00
13	0.00	0.00	0.05	0.05	0.00	0.00
14	0.00	0.00	0.05	0.05	0.00	0.00
15	0.00	0.00	0.05	0.05	0.00	0.00
16	0.00	0.00	0.05	0.05	0.00	0.00
17	0.00	0.00	0.05	0.05	0.00	0.00
18	0.00	0.00	0.05	0.05	0.00	0.00
19	0.00	0.00	0.05	0.05	0.00	0.00
20	0.10	0.10	1.00	1.00	1.00	1.00
21	0.10	0.10	1.00	1.00	1.00	1.00
22	0.10	0.10	1.00	1.00	1.00	1.00
23	0.10	0.10	1.00	1.00	1.00	1.00
24	0.00	0.00	0.05	0.05	0.00	0.00

20 Library						
Hour	Occ _WD	Occ _WE	Equi _WD	Equi _WE	Light _WD	Light _WE
1	0.00	0.00	0.05	0.05	0.00	0.00
2	0.00	0.00	0.05	0.05	0.00	0.00
3	0.00	0.00	0.05	0.05	0.00	0.00
4	0.00	0.00	0.05	0.05	0.00	0.00
5	0.00	0.00	0.05	0.05	0.00	0.00
6	0.00	0.00	0.05	0.05	0.00	0.00
7	0.00	0.00	0.05	0.05	0.00	0.00
8	0.00	0.00	0.05	0.05	0.00	0.00
9	0.25	0.50	1.00	1.00	1.00	1.00
10	0.25	0.50	1.00	1.00	1.00	1.00
11	0.50	1.00	1.00	1.00	1.00	1.00
12	0.50	1.00	1.00	1.00	1.00	1.00
13	0.50	1.00	1.00	1.00	1.00	1.00
14	0.50	1.00	1.00	1.00	1.00	1.00
15	0.50	1.00	1.00	1.00	1.00	1.00
16	0.50	1.00	1.00	1.00	1.00	1.00
17	0.50	0.50	1.00	1.00	1.00	1.00
18	0.25	0.50	1.00	1.00	1.00	1.00
19	0.25	0.50	1.00	1.00	1.00	1.00
20	0.00	0.00	0.05	0.05	0.00	0.00
21	0.00	0.00	0.05	0.05	0.00	0.00
22	0.00	0.00	0.05	0.05	0.00	0.00
23	0.00	0.00	0.05	0.05	0.00	0.00
24	0.00	0.00	0.05	0.05	0.00	0.00

Table 24 Internal Heat Gain Source Schedule for the Space Type Used in the Georgia Tech Case Study (Continued)

21 Mechanical Room						
Hour	Occ _WD	Occ _WE	Equi _WD	Equi _WE	Light _WD	Light _WE
1	0.00	0.00	0.25	0.25	0.00	0.00
2	0.00	0.00	0.25	0.25	0.00	0.00
3	0.00	0.00	0.25	0.25	0.00	0.00
4	0.00	0.00	0.25	0.25	0.00	0.00
5	0.00	0.00	0.25	0.25	0.00	0.00
6	0.00	0.00	1.00	1.00	0.00	0.00
7	0.00	0.00	1.00	1.00	0.00	0.00
8	0.00	0.00	1.00	1.00	0.00	0.00
9	0.00	0.00	1.00	1.00	0.00	0.00
10	0.01	0.00	1.00	1.00	0.01	0.00
11	0.01	0.00	1.00	1.00	0.01	0.00
12	0.01	0.00	1.00	1.00	0.01	0.00
13	0.01	0.00	1.00	1.00	0.01	0.00
14	0.01	0.00	1.00	1.00	0.01	0.00
15	0.01	0.00	1.00	1.00	0.01	0.00
16	0.01	0.00	1.00	1.00	0.01	0.00
17	0.01	0.00	1.00	1.00	0.01	0.00
18	0.00	0.00	1.00	1.00	0.00	0.00
19	0.00	0.00	1.00	1.00	0.00	0.00
20	0.00	0.00	1.00	1.00	0.00	0.00
21	0.00	0.00	1.00	1.00	0.00	0.00
22	0.00	0.00	1.00	1.00	0.00	0.00
23	0.00	0.00	1.00	1.00	0.00	0.00
24	0.00	0.00	1.00	1.00	0.00	0.00

22 Medical Office						
Hour	Occ _WD	Occ _WE	Equi _WD	Equi _WE	Light _WD	Light _WE
1	0.00	0.00	0.05	0.05	0.00	0.00
2	0.00	0.00	0.05	0.05	0.00	0.00
3	0.00	0.00	0.05	0.05	0.00	0.00
4	0.00	0.00	0.05	0.05	0.00	0.00
5	0.00	0.00	0.05	0.05	0.00	0.00
6	0.00	0.00	0.05	0.05	0.00	0.00
7	0.00	0.00	0.05	0.05	0.00	0.00
8	0.25	0.00	1.00	0.05	1.00	0.00
9	0.50	0.00	1.00	0.05	1.00	0.00
10	1.00	0.00	1.00	0.05	1.00	0.00
11	1.00	0.00	1.00	0.05	1.00	0.00
12	1.00	0.00	1.00	0.05	1.00	0.00
13	0.75	0.00	1.00	0.05	1.00	0.00
14	0.75	0.00	1.00	0.05	1.00	0.00
15	1.00	0.00	1.00	0.05	1.00	0.00
16	1.00	0.00	1.00	0.05	1.00	0.00
17	1.00	0.00	1.00	0.05	1.00	0.00
18	0.50	0.00	1.00	0.05	1.00	0.00
19	0.25	0.00	1.00	0.05	1.00	0.00
20	0.00	0.00	0.05	0.05	0.00	0.00
21	0.00	0.00	0.05	0.05	0.00	0.00
22	0.00	0.00	0.05	0.05	0.00	0.00
23	0.00	0.00	0.05	0.05	0.00	0.00
24	0.00	0.00	0.05	0.05	0.00	0.00

Table 25 Internal Heat Gain Source Schedule for the Space Type Used in the Georgia Tech Case Study

23 Retail						
Hour	Occ _WD	Occ _WE	Equi _WD	Equi _WE	Light _WD	Light _WE
1	0.00	0.00	0.05	0.05	0.00	0.00
2	0.00	0.00	0.05	0.05	0.00	0.00
3	0.00	0.00	0.05	0.05	0.00	0.00
4	0.00	0.00	0.05	0.05	0.00	0.00
5	0.00	0.00	0.05	0.05	0.00	0.00
6	0.00	0.00	0.05	0.05	0.00	0.00
7	0.00	0.00	0.05	0.05	0.00	0.00
8	0.00	0.00	0.05	0.05	0.00	0.00
9	0.10	0.25	1.00	0.05	1.00	0.00
10	0.25	0.50	1.00	1.00	1.00	1.00
11	0.50	1.00	1.00	1.00	1.00	1.00
12	0.50	1.00	1.00	1.00	1.00	1.00
13	0.50	1.00	1.00	1.00	1.00	1.00
14	0.50	1.00	1.00	1.00	1.00	1.00
15	0.50	1.00	1.00	1.00	1.00	1.00
16	0.50	1.00	1.00	1.00	1.00	1.00
17	0.50	1.00	1.00	1.00	1.00	1.00
18	0.50	1.00	1.00	1.00	1.00	1.00
19	0.10	0.25	1.00	1.00	1.00	1.00
20	0.00	0.00	0.05	0.05	0.00	0.00
21	0.00	0.00	0.05	0.05	0.00	0.00
22	0.00	0.00	0.05	0.05	0.00	0.00
23	0.00	0.00	0.05	0.05	0.00	0.00
24	0.00	0.00	0.05	0.05	0.00	0.00

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VITA

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Mr. Lee was born in Daegu, South Korea. He received a B.A. in Architectural Engineering from Kyungpook National University, Daegu, South Korea in 2002 and a M.A. in School of Building Construction, College of Architecture from Georgia Tech, Atlanta, Georgia in 2005. During the Masters study, his major focus was about the integrated facility management, and he was employed at the Georgia Tech Facilities. His main tasks were analyzing energy data from utility companies for campus buildings, which brought his interest in energy consumption management and performance assessment in campus-scale. His focus on campus-wide energy related facility management study brought him a Facility Management Professional (FMP) designated by International Facility Management Association (IFMA) in 2004.

He joined High Building Performance (formerly Building Technology) Ph.D. program led by Prof. Godfried Augenbroe in Georgia Tech College of Architecture. He continued his research in the field of a building energy performance evaluation broadening to large-scale. He had been involved many building energy performance research projects such as:

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His profound concentration on energy performance evaluation brought development of building scale: Energy Performance Standard Calculation Toolkit (EPSCT), and large-scale: Energy Management Dashboard. He published several journal and conference papers with his research works in projects and thesis.